M.Sc. Thesis

DEVELOPMENTS IN FABRICATION AND NOISE MEASUREMENT (AT 20 MC/S) OF INSULATOR DIODES.

by

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LIST OF SYMBOLS

\( T = \) absolute temperature
\( V = \) applied voltage
\( d = \) crystal thickness
\( \rho = \) charge density
\( \varepsilon_0 = \) absolute permittivity of vacuum
\( \varepsilon = \) absolute permittivity of crystal
\( J = \) current density
\( v = \) electron velocity
\( m = \) mass of electron
\( \Phi_M = \) work function of metal
\( \chi = \) electron affinity of crystal
\( \Phi = \) work function of crystal
\( E(x) = \) electric field intensity
\( n = \) density of free electrons; index of the power of the law \( I \propto V^n \)
\( \mu = \) electron mobility
\( D = \) Einstein diffusion coefficient
\( \Phi_A = \) work function of anode material
\( V_0 = \) threshold voltage
\( i = \) current
\( A = \) area of electrodes
\( N_c = \) density of space charge electrons at the cathode
\( N_o = \) effective number of states averaged over the conduction band
\( k = \) Boltzmann's constant
\( V_s = \) transition voltage between s.c.l. current and proportional current.
\( N_t = \) density of electron traps
\( V_T = \) traps-filled voltage limit
\( n_t = \) density of filled traps
\( W_t = \) energy depth of traps below conduction band
\[ W_F = \text{energy depth of Fermi level below conduction band} \]
\[ \theta = \text{ratio of free electron density to total electron density} \]
\[ \delta f = \text{bandwidth} \]
\[ E = \text{e.m.f.} \]
\[ P = \text{power} \]
\[ R = \text{diode a.c. resistance} \]
\[ C = \text{diode capacitance} \]
\[ I_o = \text{d.c. current through noise diode} \]
\[ I = \text{d.c. current through crystal diode} \]
\[ T^2 = \text{smoothing factor} \]
\[ F = \text{noise factor} \]
\[ f = \text{ratio of mean square crystal current to mean square noise generator current} \]
\[ Z = \text{complex impedance} \]
\[ Y = \text{complex admittance} \]
CHAPTER I

Introduction.

The resistivity of a solid is its fundamental electrical property. Although resistivity covers a greater range of values than any other property — varying between $10^{-6} \Omega$-cm for a good conductor and $10^{17} \Omega$-cm for an insulator, the solids are not evenly distributed throughout this range. Most appear at the extreme ends of the range and only a few in the middle. This is fortunate in one respect, because the proliferation of conductors and insulators must have helped in the early development of electricity. However, the lack of materials in the middle of the range delayed the investigation of an important group of materials known as the semiconductors. A further delaying factor was the scientist's inability to purify such materials to a point where impurities no longer masked the inherent properties. This difficulty was overcome a few years ago by the discovery of "zone-refining", a process which uses the fact that impurities are more soluble in the molten material than in the solid. Purities of one part in $10^{30}$ can be obtained by this method, whereas chemical methods can only produce purities of one part in $10^8$.

The rough division of solids into three groups — conductor, semiconductor, and insulator was appreciated long before the grouping was explained. It was not until approximately 30 years ago, when the band theory of solids was proposed, that a satisfactory explanation was available. The band theory states that the electrons in a crystalline solid can only have energies within certain ranges. In between these ranges are forbidden bands of energy. A simplified explanation can show how this comes about. In an atom of hydrogen the single electron can be thought of as in a potential well and having a certain energy. When another atom is brought near the first, the
combination of the two potential wells results in a splitting of the original energy level and the two electrons will have energies very slightly different from each other. If a third hydrogen atom is brought near the original level is split into three and so on. Thus, for a large collection of hydrogen atoms, the original energy level is split into a set of energy levels all quite close to each other, that is a band of energy levels. However, only one of the possible discrete energy levels of the hydrogen atom has been considered and it has several. Thus, for each energy level of the free hydrogen atom there will now be a band of energies and these will be separated by forbidden regions. A similar effect occurs for all atoms except that it is possible for bands to overlap. The electrons contained in the mass of the material fill these energy levels occupying the lowest levels first. All the electrons cannot go into the lowest energy levels because, by Pauli's Exclusion Principle not more than two electrons in the crystal can have the same energy. Thus an allowed band can hold no more than a fixed number of electrons. It is possible using this simplified idea of band structure to understand the difference between metals, insulators and intrinsic semiconductors.

In a metal, one of the allowed bands is not completely filled so that by thermal excitation and applied voltage electrons can easily move up into empty states and be conducted through the crystal. In an insulator, on the other hand, a certain number of the
allowed bands are completely filled, and there are no empty states available for electrons to rise into, since the forbidden gap is too large for an electron to jump. Of course, there will always be a finite probability, at temperatures different from zero, that some electrons will be excited up into the next empty band (the "conduction band") but if the gap is large e.g. 7 eV for diamond, then for all practical purposes the material is an insulator. For an intrinsic semiconductor the forbidden gap is not so large (about 1 eV) and at room temperature a useful number of electrons can be thermally excited into the conduction band.

It is one of the results of the modern theory of solids that an electron can move freely without being deflected in any periodic electrostatic field. Such a field would exist in a perfect crystal lattice, in which all the atoms were at rest. Thus an electron, having energy permissible by the band theory, should be able to move freely through an insulator crystal. To make practical use of this, sufficient electrons would have to be introduced into the allowed bands of the crystal from an external source and it should then be possible to obtain space-charge-limited (s.c.l.) current through the crystal. The current would be space-charge-limited since, as in the case of the s.c.l. thermionic vacuum diode, the number of electrons able to get into the space between cathode and anode would be limited by a repelling space charge field. Normally, s.c.l. currents are not obtained through an insulator crystal, for two reasons. Firstly, due to the difference in magnitude between the work function of the metal cathode and the electron affinity of the crystal, there is usually a surface potential step of sufficient size to prevent many electrons from entering the crystal. Secondly, it is not possible to grow perfect crystals. Even the best crystals contain lattice defects and some of these act as trapping centres.
for electrons. The trapped electrons are no longer available for carrying current besides which they set up a repelling field, which further reduces current flow.

Although it is only recently that these problems have been solved and s.c.l. currents in insulating material have been realised in practice, theories on the subject have been in existence much longer. In 1940 Mott & Gurney\(^{(1)}\) predicted that in a perfect crystal with ideal contacts the s.c.l. current should be proportional to the square of the applied voltage and at sufficiently high voltage, when the available space charge is moved across, the current should become proportional to the applied voltage. For the more realistic conditions of non-ideal crystals, the effects of the electron trapping centres have been considered in papers by Rose\(^{(2)}\) and Lampert\(^{(3)}\). In a paper in 1955 Skinner\(^{(4)}\) discussed the flow of current in an ideal crystal between electrodes of different work functions and showed that rectification should be obtained.

The first observation of s.c.l. currents in insulator diodes was recorded by Smith & Rose\(^{(5)}\) in 1955. They reported observing transient currents in cadmium sulphide crystals that could not be accounted for as ohmic currents. More recently G.T. Wright\(^{(6)}\) has obtained steady and reproducible currents through insulating crystals of cadmium sulphide and Allen & Cherry\(^{(7)}\) have reported s.c.l. currents in gallium arsenide.

In 1961, insulator diodes were successfully constructed by the author\(^{(8)}\) using cadmium sulphide crystals with an indium cathode and colloidal graphite anode. However, although successful, these diodes were rather fragile and had to be handled with care. This year, work in this laboratory has been concerned firstly with the production of more robust insulator diodes. These were constructed
on 9-pin valve bases and metal electrodes were vacuum-coated on to the
exposed faces of the crystal. Cathodes of indium were used throughout.
Gold and silver were tried as anodes. Successful diodes were made by
this method and they proved to be much more robust than the previous
type, as there were very few breakages from handling them. The second
purpose of the work was an investigation into the noise properties of
insulator diodes. Noise measurements were made on some of the
successful ones and, as in the previous year\(^8\)(9), values of
smoothing factor less than unity were obtained. All the results were
examined together in order to determine whether there was any
correlation between the values of smoothing factor and the values of
other parameters.
CHAPTER II

Theory of Space-Charge-Limited Currents

The Vacuum Diode

Consider the hypothetical diode consisting of two infinite parallel planes, in which electrons leave the cathode with zero velocity. At a very low cathode temperature, there will be a negligibly small number of emitted electrons and a steady potential difference across the plates will result in a uniform electric field. This potential distribution is shown by curve $T_1$ in Fig. 2.1.

As the cathode temperature is increased to a value $T_2$ and more electrons are emitted into the space between the plates, the negative charge of these electrons decreases the potential distribution, as shown by curve $T_2$ of Fig. 2.1. The end points of the curves remain fixed since the difference of potential between the electrodes is fixed. In both cases, $T_1$ and $T_2$, all the electrons are drawn to the anode, since the electric field, given by the negative of the slope of the potential plot, always accelerates the electrons towards the anode at any point within the diode. Under these conditions, the diode is said to be temperature-limited since, when the voltage $V$ between cathode and anode is so high that all the emitted electrons reach the anode,
the temperature of the emitter determines the amount of current.

If the temperature of the cathode is raised sufficiently, the potential distribution will be further depressed to the curve marked \( T_3 \) in Fig. 2.1. For this particular value of temperature the slope of the potential plot is zero at the cathode. This is due to the increased number of electrons whose electric field neutralises the applied field at the cathode.

In practice the electrons leave the cathode with a finite velocity and so if the temperature of the cathode is raised still further, to temperature \( T_4 \), the amount of charge accumulating near the cathode will be so large that the potential curve will exhibit a negative dip as shown in Fig. 2.1. In this case the resultant field at the cathode will be retarding and the emitted electrons must possess sufficient initial velocity to get through this retarding field and reach the anode. Those electrons which are emitted without enough velocity are repelled back to the cathode. Once the potential minimum has formed, the current reaching the anode is almost completely independent of the cathode temperature, because any increase in the number of emitted electrons is virtually counteracted by the resulting increase in the space-charge cloud, which repels more electrons back into the cathode. Thus, the cases of \( T_3 \) and \( T_4 \), where the slope of the potential curve becomes zero at some point between the cathode and anode, are examples of space-charge-limited operation.

In general, it is desirable to have the current dependent only upon the applied voltage and not upon the temperature of the emitter. Temperature dependence of the current leads to erratic operation, since it is difficult to maintain a desired emitter temperature. Furthermore, emitters have shorter lives when run at saturation. On the other hand, a given potential difference between anode and cathode
can be established quite easily. Hence vacuum tubes are usually operated in the space-charge-limited regime.

In order to analyze the operation of an s.c.l. vacuum tube, an expression relating the potential distribution to the distribution of charge within the diode is needed. Such an expression is provided by Poisson's equation, which for the one-dimensional problem is

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon_0} \quad \ldots \quad (2-1)$$

where $V$ is the potential at a distance $x$ from the cathode and $\rho$ is the charge density there.

To solve this differential equation, the space charge density $\rho$ must be related to the potential $V$ through additional equations. The continuity equation states that

$$J = -\rho v \quad \ldots \quad (2-2)$$

where $v$ is the electron velocity and $J$ is the current density. $J$ must be a constant with respect to the distance $x$, otherwise charge would build up in some region between the electrodes and this violates the steady state assumption.

Combining these equations,

$$\frac{d^2V}{dx^2} = \frac{J}{\varepsilon_0 v} \quad \ldots \quad (2-3)$$

The electron velocity $v$ is related to the potential by the equation

$$v = \sqrt{\frac{2eV}{m}} \quad \ldots \quad (2-4)$$

assuming $v = 0$ for $V = 0$ so that

$$\frac{d^2V}{dx^2} = \frac{J}{\varepsilon_0} \sqrt{\frac{m}{2eV}} \quad \ldots \quad (2-5)$$

This expression may be solved by multiplying both sides by $2 \frac{dV}{dx}$ and then integrating w.r.t. $x$. 
\[
\int 2 \frac{dV}{dx} \cdot \frac{d^2V}{dx^2} \, dx = \int \frac{2J}{\varepsilon_0} \sqrt{\frac{m}{2e}} \cdot V^{-\frac{1}{2}} \, dV
\]

where the constant of integration is zero, if the slope of the potential distribution is zero for \( V = 0 \). Integrating again,

\[
J = \frac{4e \Omega}{9} \sqrt{\frac{2e}{m}} \cdot \frac{V^{3/2}}{x^2} \; \text{amps/unit area.} \quad (2 - 6)
\]

This is the Child-Langmuir Law of space-charge-limited flow, which states that the current varies as the three-halves power of the anode potential and inversely as the square of the electric spacing.

This analysis has assumed that the minimum of potential occurs at the cathode and that all electrons have exactly the same velocity along any plane parallel to the electrodes. This is not usually the case in practical diodes, where the temperature of the cathode is normally greater than that corresponding to \( T_3 \) in Fig. 2.1. The analysis may be extended when a potential minimum exists elsewhere by assuming that the cathode is at the plane of the potential minimum. This hypothetical cathode is known as the "virtual cathode". The anode potential is then taken as the difference in potential between the anode and the virtual cathode and the distance \( x \) is similarly modified. Often, the potential minimum is small compared to the anode potential and is comparatively close to the cathode. In such cases the Child-Langmuir equation may be used fairly accurately without making adjustments to \( V \) or \( x \).

The crystal diode.

If electrons can be introduced from a metal cathode into the conduction band of an insulator, then it should be possible to obtain s.c.l. current. The reason why this does not happen in general is
probably that the highest occupied state of the electron in the metal at normal temperatures is well below the lowest conduction band level of the insulator. Electrons can thus only leave the metal and pass into the insulator under the same conditions as from the metal into vacuum, i.e., either very large fields or very high temperatures would be required in order to obtain observable current. However, it is possible to obtain a situation where the difference between the work function of the metal $\Phi_M$ and the electron affinity of the crystal $\chi$ is fairly small — say of order of $\frac{1}{2}$ eV. (It is defined as the energy difference between the lowest conduction level and vacuum.)

Then, even at room temperature, some thermionic emission from metal to insulator should be possible. R. W. Smith (10) examined the problem of metal contacts on to insulating crystals of CdS. He found that Ag, Cu, Au, C and Pt do not make ohmic contact to CdS, whereas In and Ga do. This he correlated with the fact that only In and Ga have smaller work functions than CdS. If $\Phi_M < \Phi$ as was true for In and Ga then it follows that $(\Phi_M - \chi) < \frac{1}{2}$ forbidden gap i.e. $< 1.24$ eV. Thus, the experimental evidence tends to confirm the idea that ohmic contacts occur when $(\Phi_M - \chi)$ is small.

Consider what happens when the metal is brought into contact with the insulator. If the work function of the crystal $\Phi$ is greater than $\Phi_M$, an ohmic contact is defined as one which has no rectifying action.
that of the metal, then electrons will transfer from the metal to the insulator, since this will reduce the energy of the system. The transfer will take place until the Fermi levels equalize, which is the equilibrium state. Thus, there will be a cloud of electrons in the conduction band of the insulator and an equal positive charge will be formed on the surface of the metal. In the body of the insulator, as the Fermi level is raised, so also are the conduction and valence bands. However, at the boundary of the crystal and the metal, the dipole layer of charge creates a field which depresses the energy levels of the insulator near the boundary. The energy level diagram is then as in Fig. 2.3.

![Fig. 2.3](image)

The Fermi level is not depressed since in equilibrium conditions the flow of electrons to the left due to the field of the dipole layer is balanced by the diffusion of electrons to the right, as a result of the concentration gradient.

Application of a voltage across the crystal will cause the conduction band to move to the dotted line position in Fig. 2.3, and the electrons in the conduction band near the metal/insulator interface will be drawn through the crystal lattice. The current
density at a distance x from the metal cathode is the algebraic sum of the drift and diffusion current densities. Thus if the electric field in the crystal is $E(x)$

$$J = ne\mu E - eD \frac{dn}{dx}$$

However, in practice the diffusion current may be neglected in comparison with the drift current, if the potential across the crystal is large compared with 0.025 volts (Ref. (1) p.172). Thus

$$J = ne\mu E \quad \ldots \ldots \quad (2-8)$$

In addition Poisson's equation for the one-dimensional problem is

$$\frac{dE}{dx} = \frac{ne}{\varepsilon} \quad \ldots \ldots \quad (2-9)$$

Combining by eliminating $ne$ gives

$$J = e\mu \frac{dE}{dx} \quad \ldots \ldots \quad (2-10)$$

and hence integrating

$$Jx + \text{const} = e\mu \int E^2$$

If we ignore for the moment the possibility of a virtual cathode and assume the electric field to be zero at $x = 0$ then the constant of integration will be zero.

Thus,

$$E = -\left(\frac{2J}{\varepsilon\mu}\right)^{1/2} x^{1/2} \quad \ldots \ldots \quad (2-11)$$

where the negative square root has been chosen since $E$ is in negative direction $x$. Integrating again

$$V - \Phi_A - \Phi_M = - \int_0^d \text{Edx} = \frac{2}{3} \left(\frac{2J}{\varepsilon\mu}\right)^{1/2} d^{3/2}$$

where $\Phi_A$ is work function of the anode material and $d$ is the crystal thickness. Writing $\Phi_A - \Phi_M = eV_0$ and $i = JA$,

$$i = \frac{9}{8} \left(\frac{e\mu A(V - V_0)^2}{d^3}\right) \quad \ldots \ldots \quad (2-12)$$

This equation represents the Child-Langmuir law for solids. No appreciable current will flow until a threshold voltage of magnitude

$$\Phi_A - \Phi_M \quad \ldots \ldots \quad \frac{\Phi_A - \Phi_M}{e}$$

has been passed, after which the square root of the current
should increase proportionally to the applied voltage. The slope of the applied voltage vs (current) \( \frac{1}{2} \) graph is given by \( \frac{9e\mu A}{8d^2} \) and therefore depends on electrode area and crystal thickness.

The equation (2-12) describes the relation between current and voltage when the crystal diode works in the space-charge-limited régime. If, however, a sufficiently high voltage is applied then this equation no longer applies, since all the electrons issuing from the cathode will be swept across the insulator. Then the current will depend only on what is available from the cathode reservoir and not on the space charge between the electrodes. For very high voltages, the electric field will be uniform throughout the crystal. Thus,

\[
J = n\mu E
\]

where \( E = \frac{V}{d} \) and \( n \) will be the equilibrium density of space charge electrons, which at the cathode is

\[
N_c = N_0 \exp \left( - \frac{\Phi_n - \Phi_F}{kT} \right)
\]

where \( N_0 \) is effective number of states averaged over the conduction band of the crystal. The exponential factor is an approximation of the Fermi distribution function. Therefore, as the threshold voltage is negligible

\[
i = \frac{N_c e\mu AV}{d} \quad \text{... (2-13)}
\]

and the current is now proportional to the voltage.

The approximate transition voltage between s.c.l. current and proportional current occurs when the two equations (2-12) (2-13) give the same current. Then,

\[
V_s = \frac{8}{9} \frac{eN_c d^2}{\varepsilon} \quad \text{... (2-14)}
\]
The above theory, which results in the Child-Langmuir Law for solids (Eqn. 2-12) makes one assumption that has not been mentioned so far. In eqn. (2-8), the drift current density is given in terms of the variable electric field. It has been assumed that the mobility is a constant. However, in fact, the mobility decreases for high electric fields, and this could effect the accuracy of the derived equations.
The non-ideal crystal

The above treatment of the insulator diode follows essentially that of Mott & Gurney (1) and takes no account of crystal lattice imperfections. Certain lattice defects that may exist in the crystal act as trapping centres for electrons. It is easy to see how trapped electrons may modify the simplified theory. For example, if there were a uniform density of traps $N_{t}$, all filled, these would set up a space charge field intensity of magnitude given by Poisson’s equation:

$$\frac{dE}{dx} = \frac{N_{t}e}{\varepsilon}$$

or

$$E(x) = \frac{N_{t}ex}{\varepsilon}$$

and hence a potential difference $V_{T} = \frac{N_{t}ed^{2}}{2\varepsilon}$ across the crystal. Thus, it would be expected that, until the applied voltage exceeded this value, the current would be smaller than the full s.c.l. value.

If the density of initially empty electron traps is $N_{t}$ at a depth $W_{t}$ below the conduction band, then, when current occurs, the density of filled traps is

$$N_{0} = \frac{N_{t}}{\frac{W_{t} - W_{c}}{kT}}$$

where $W_{c}$ is depth of Fermi-level below conduction band. The equilibrium density of conduction electrons is

$$n = \frac{N_{0}}{1 + \frac{W_{c}}{kT}} \approx N_{0} \frac{W_{c}}{kT}$$

where $N_{0}$ is the effective integrated density of conduction levels and may be taken as $N_{0} = 2(\frac{2\pi m^{*}kT}{h^{2}})^{3/2} \approx 10^{25}/m^{3}$ at room temperature. Therefore, the ratio of mobile to trapped electrons is

$$\text{for an applied potential } V_{T} \text{ sufficient to cancel the repelling field at the cathode.}$$
If the traps lie at least several kT below the Fermi level then they may be regarded as deep traps. For such traps \( W_t \gg W_f \) and the ratio of free to trapped electrons is

\[
\frac{n}{n_t} = \frac{N_0}{N_t} e^{rac{-W_t}{kT}}
\]

Lampert(3), who has considered this case, has shown that only a very small proportion of the injected space-charge remains free. Further the amount of space-charge varies from place to place in the crystal and depends on the magnitude of the current.

Traps which lie at least several kT above the Fermi-level may be regarded as shallow. In this case \( W_f \gg W_t \) and

\[
\frac{n}{n_t} = \frac{N_0}{N_t} e^{rac{-W_t}{kT}}
\]

Such traps have the property of leaving free a fixed proportion \( \theta \) of the space-charge injected into the crystal

\[
\theta = \frac{n}{n + n_t} = \frac{1}{1 + \frac{n_t}{n}} = \frac{N_0}{N_0 + N_t e^{rac{-W_t}{kT}}}
\]

Such traps will reduce the magnitude of the current but the form of the current-voltage characteristic will remain unaltered since \( \theta \) is a constant. The influence of these traps can be taken into account by defining an effective permittivity \( \varepsilon \theta \) instead of \( \varepsilon \) so that equation (2-12) becomes

\[
\frac{i}{d} = \frac{\sigma \varepsilon \theta \mu A (V - V_o)^2}{d^3}
\]

This is the modified Child's Law region.
If an insulator diode contains both deep and shallow traps then its current-voltage plot is quite complicated. At small applied voltages the charge injected into the crystal is small. Most of this charge falls into deep traps and so currents are very small and non-linear. This is the deep trap limited region in Fig. 2.4.

As the applied voltage rises, more charge is injected into the crystal and eventually a voltage $V_{T1}$ is reached at which all deep-lying traps are filled. At this point the current rises extremely rapidly. This is the traps filled region in Fig. 2.4. For a $10\mu$ CdS crystal, the density of deep electron traps might be $10^{20}/m^3$ in which case $V_{T1}$ would have a value of $\sim 9V$ by equation (2-15). In order to obtain useful current at small voltages, the number of deep traps must be
kept as small as possible.

Following on this rapid rise in current, the current is space-charge-limited and follows a modified square law lying just below the theoretical square law. The shallow traps might have a density of $10^{21}/m^3$ which means that at a voltage of approximately 90V the current rises rapidly again to the full Child's Law value. After voltage $V_{T2}$ the current follows this law until, at very high potentials, when the whole space charge is moved across, the current becomes proportional to the voltage.

The cathode contact

As mentioned in a previous section, Smith\(^{(10)}\) maintained that barrier contacts to CdS crystals resulted when the electrode metal had a greater work function than CdS. However, various experiments have shown that an alternative viewpoint is possible. Buttlar & Muscheid\(^{(11)}\) showed that ohmic contact could be made to CdS crystals with a variety of metals, if the contact area were first subjected to electron bombardment. Similarly Passbender\(^{(12)}\) reported that ohmic contacts could be formed by subjecting the contact area to ionic bombardment by an electric discharge. These results show that it is possible to think of the contact barrier as being caused by the surface states on the CdS itself. Kröger et al.\(^{(13)}\) pointed out that In and Ga are both n-type impurities in CdS, whereas other metals like Cu, Ag and Au, which do not form ohmic contacts, are p-type impurities. Kröger argued, therefore, that the ohmic contacts found with In and Ga on n-type CdS, were the result of a diffusion of the In or Ga into the CdS around the contact in the process of making the contact, so as to form a highly n-type region facilitating the occurrence of ohmic behaviour.
How does this n-type region produce the effect of an ohmic contact? The material in contact with the metal cathode is an n-type semiconductor, in which the Fermi-level lies between the donor levels and the lowest level of the conduction band. Since the donor levels lie very near the conduction band, the Fermi-level is just below the conduction band and is therefore above the Fermi-level of the metal before contact. On contact with the metal, electrons are transferred from the donor centres to the metal, leaving a thin barrier layer containing a fixed positive space charge. The potential drop through this barrier equalises the Fermi levels of the metal and the semiconductor layer. In this region the conduction band is lowered along with the Fermi-level as shown in Fig. 2.5.

![Fig. 2.5](image)

The barrier is thin enough to be virtually transparent to electrons and so thermal diffusion of electrons occurs into the insulating bulk of the crystal until the electric field set up is sufficient to prevent further diffusion. The Fermi-levels of metal and crystal are then equalised. This space charge of electrons will act as an easily replenished reservoir. When a voltage is applied across the crystal, electrons are drawn from this reservoir across the crystal giving s.c.l. current.
The two most important kinds of electrical noise are:

(i) Thermal noise (Johnson, Nyquist or resistance noise) caused by the random thermal motion of the charge carriers.

(ii) Schottky (Shot) noise, which is due to the fluctuation of the current caused by random emission of charge carriers.

**Thermal noise**

The thermal motion of the electrons in a resistor does not produce a d.c. e.m.f. across it since the motion is quite random and the mean effect will be zero. However, the r.m.s. voltage is not zero, and this voltage can be used to deliver power to another resistor. Nyquist, by consideration of the statistical thermodynamics of the problem, was able to state that the maximum power that any resistance could deliver to an external load was

\[ P = \frac{kT \Delta f}{2} \]

where \( T \) is absolute temperature, \( \Delta f \) is the bandwidth of the system and \( k \) is Boltzmann's constant. By the maximum power theorem, the maximum power delivered by a resistance \( R \) will be to an equal resistance \( R \).

Consider the system to be as in the diagram:

![Diagram of a circuit with a resistor \( R \) and a noise source with e.m.f. \( E \) and bandwidth \( \Delta f \).]

The mean square value of the e.m.f. over a range \( \Delta f \) is \( E^2 \Delta f \) and so the mean square value of the corresponding current is

\[ i^2 \Delta f = \frac{E^2 \Delta f}{(2R)^2} \]

Power delivered to the second \( R \) is therefore
\[
P_{\Delta f} = \frac{i^2}{\Delta f} R = \frac{E^2}{4R^2} \Delta f \cdot R = \frac{E^2}{4R} \Delta f
\]

and using the previous result, this must equal \(kT\Delta f\).

Thus
\[
\frac{E^2}{\Delta f} = 4kT\Delta f
\]

This is the mean square noise voltage developed across a resistance \(R\).

Similarly, by considering the noise source to be a current generator with a resistance \(R\) in parallel, this system will also deliver maximum power to an equal resistance. The system is as follows:

![Diagram of the noise source with a current generator and a resistance in parallel.]

The mean square value of the current generated over a range \(\Delta f\) is \(\frac{i^2}{\Delta f}\) and so the mean square current through the second \(R\) is \(\frac{i^2}{\Delta f} \cdot \frac{R}{4}\). The power delivered to this \(R\) is therefore:

\[
P_{\Delta f} = \frac{i^2}{\Delta f} \cdot \frac{R}{4}
\]

and equating this to \(kT\Delta f\),

\[
\frac{i^2}{\Delta f} = \frac{4kT\Delta f}{R}
\]

**Shot Noise**

The principal reason why vacuum tubes contribute noise to a system is that the current is formed by the random arrival of discrete electric charges at the anode. It is the random arrival times that contributes most of the noise spectrum; the discreteness of the charges alone would not produce much noise. This noise is called "shot" noise because of the resemblance of electron flow to a stream of small shot.
Shot noise differs from thermal noise in several respects. (i) The average current is not zero as in the case of thermal noise but is equal to the d.c. value of anode current. (ii) The system is not in thermal equilibrium as in the thermal noise case since energy is continually supplied to the cathode to produce emission of electrons. Therefore, the principles of thermodynamics cannot be used here as they were for thermal noise. Instead, the problem is approached from statistical consideration of the randomness.

There are two cases to consider here. The first is temperature limited emission when all the electrons emitted are drawn to the anode. Under these conditions, the mean square noise current is given by

\[ i^2_{\text{shot}} = 2eI_o \Delta f \]

where it is assumed that there is instantaneous transfer of charge across the valve. \( I_o \) is the emission current in amps and \( \Delta f \) is the bandwidth of the system. Since the valve is in the saturated mode of operation, the independence of anode current relative to anode voltage means that the slope of the current vs voltage curve is zero and hence the a.c. impedance of the tube is infinite. Thus, such a diode is a pure current source, i.e. one with an infinite shunt impedance. Thus, if this noise is fed into an external resistor \( R \), there is an effective noise power of \( i^2_{\text{shot}} R \) in the resistor. Such a noise source can be used as a standard.

The other case to consider is when the d.c. current in the valve is space-charge-limited. In this case, the noise is less than predicted above and is given by

\[ i^2_{\text{shot}} = 2eI_o \phi^2 \Delta f \]

where \( \phi^2 \) is the smoothing factor. This smoothing action is due to the presence of the virtual cathode in front of the emitting surface. In a previous section, it was shown how the potential minimum, present in the s.c.l. current case, caused the current to be virtually
independent of cathode temperature. This occurred because any increase in emission caused the repelling space charge to increase and this cancelled out any increase in current that would have occurred. This mechanism also works in the steady state operation of a valve. If a greater number of electrons than average is emitted in a certain velocity group, then the average space charge increases and causes the potential barrier to increase. This has the effect of repelling more electrons than usual and hence minimises the effect of the original burst of electrons. The effect of the random variations of electron emission is therefore reduced and the noise is reduced relative to the full shot noise case.

**Noise factor.**

It was mentioned in the previous section that a temperature-limited diode could be used as a standard noise source. Such a noise source would be calibrated in noise factor. A relation between this noise factor and the d.c. anode current through the noise diode is required.

The noise factor of a receiver is defined as

\[ F = \frac{\text{signal/noise at input}}{\text{signal/noise at output}} \]

To measure this in practice, the diode is connected with suitable d.c. isolation across the receiver input, which is also shunted by the resistor R. The noise output of this diode is increased until the noise output of the receiver alone is doubled. Under these conditions, the signal to noise ratio at the output is unity, and the noise factor is then the ratio of the noise diode mean square voltage across the resistor R to the thermal noise of the resistor R.

\[ F = \frac{2eI_o \Delta f R^2}{4kTR \Delta f} \]

\[ = \frac{e}{2kT} I_o R \]

At room temperature \((T = 290^\circ A)\), \(kT\) has the convenient value of
4 \times 10^{-21} \text{ Joules and } e = 1.6 \times 10^{-19} \text{ coulombs. Thus}

F = 20I_o R
CHAPTER III

The experimental work falls into two categories. Firstly, the production of robust insulator diodes and secondly the study of their noise properties. To accomplish the first aim, various approaches to diode construction were tried until a successful method was achieved that was reasonably consistent. The success of each effort was judged by the steadiness of the characteristic of current vs voltage, and whether reasonably large current was obtained at low voltage. The voltage current relationship was considered in each case and also the reverse current/voltage plot. Measurements were taken of the a.c. resistance and capacitance of the diodes. To further the second aim, several successful diodes were regarded as noise sources and were compared with a standard temperature-limited noise diode to assess the smoothing effect. Values of $r^2$ for 5 mA anode current were obtained and compared with regard to the various crystal parameters to find whether any law held for the values of $r^2$.

Experimental diode construction.

Throughout the work done in this laboratory, the insulator crystal has been cadmium sulphide. CdS crystals can grow as close-packed hexagonal or as face-centred cubic crystals. In each the line of cleavage is parallel to the C-axis. The crystals are grown from the powder by the vapour phase technique and crystallise either in needle form or in the form of flat yellow plates. The powder is heated in a furnace to a temperature between 970 - 1000°C in a gentle flow of nitrogen, which carries the vapour to cooler parts of the tube where crystals grow. Growth periods are from 1½ to 2 hrs.
By correct adjustment of the growing conditions, it is possible to grow the majority of crystals in the plate form. The thicknesses can vary from a few microns to several hundreds of microns, although those grown in this laboratory were typically between 10 and 70 microns. All the crystals used in making diodes were grown in this laboratory by Mr. Sinharay. Cds is an insulator commonly having a dark resistivity of the order of $10^{12}$ $\Omega \cdot$ cm, and has a forbidden gap of width 2.48 eV at room temperature. The work function of the crystal is estimated as $\phi_{\text{CdS}} = 4.2$ eV assuming $\phi_{\text{Au}} = 4.9$ eV (5). When the crystal is made n-type semiconductor by the diffusion of In or Ga, the donors have ionisation energies of the order of 0.05 eV.

The metal used for the cathode, throughout these experiments, was indium (melting point 155°C). This metal is supplied in wire form and is oxidised on the surface. The metal is soft and can be readily scraped to expose the clean shiny metal underneath. It remains shiny and unoxidised for several days, thus facilitating its use for the various contacts. The work function of In is estimated to be between 3-4 eV which is less than $\phi_{\text{CdS}}$.

Both gold and silver were used as anode metals. Like the In, they were supplied in the form of wire. Silver has a work function of 4.5 eV and evaporates at 1319°C. Gold has a work function of 4.9 eV and evaporates at 1345°C.

The diodes were constructed on B9A valve bases, which were kindly supplied by Mullard Limited. These bases consisted of nine rigid pins sealed through a glass disc and leading on to soft metal leads. The soft leads were clipped off and the glass base filed flat. A hole, just larger than 1 mm. diameter, was bored vertically
through the glass disc using a diamond tipped drill lubricated with pure turpentine. This hole was then carefully opened out - chamfered on the pin side, using a tungsten carbide drill again with pure turpentine as the lubricant. The base was then scrubbed in carbon tetrachloride to remove the turpentine and glass dust.

(Red areas show presence of FSP49)

Fig. 3.1.

In order to ensure good electrical contact between the pins and the evaporated metallic films, some silver-loaded araldite was placed at the filed ends of the pins and at the junction of pins and the glass, as shown in Fig. 3.1. The araldite was thermo-setting silver cement FSP49. The cement is supplied in two separate components both containing silver in the form of flake. A 50/50 mixture was used and this was cured by stoving at 100°C for the recommended time of 20 - 30 mins.

The CdS crystals were handled easily by using a "Speedivac" water jet pump to create a suction at the end of a narrow bore tube. The crystals could be easily picked up by the suction tube and moved
around at will. The thickness of a CdS plate crystal was measured using a microscope in the horizontal position. The crystal was placed flat on the edge of a slide so that the microscope was looking at the crystal edge on. Using the microscope at 400 magnification, the thickness was measured in terms of the graticule scale. This scale was then compared with a stage micrometer slide with divisions of 0.1 and 0.01 mm. Measurements could be made by this method to an accuracy of less than a micron. Having measured the crystal thickness a prepared valve base was taken and ordinary araldite spread in the hollow on the filed face of the base. Using the suction tube, the crystal was carefully placed over the hole in the base so that both faces of the crystal were accessible. The araldite was then hardened by placing the base in a furnace at 100°C for 20 mins.

The next stage in the process involved the vacuum coating of both sides of the crystal with suitable metals. This process was carried out in a "Speedivac" coating unit. This unit comprises a glass workchamber which is evacuated by an oil vapour diffusion pump, backed by a single stage gas ballasted rotary pump. Also incorporated are low-tension supplies for filament heating and a high tension unit for use in ion bombardment. For the early experiments a cylinder of brass sheet was fitted round one of the low tension terminals with a top cap to go over this so as to contain the evaporation in a reasonable volume. This prevented the metal coating all the surfaces in the work chamber and so reduced cleaning time. The top cap had nine holes punched in it corresponding to the pins of the valve base and a rectangle of metal was cut out joining pins 1 and 6 rather like Fig. 3.2(a) on p. 33. The filament first fitted was a tungsten
helix, but this was very dirty when "flashed" and furthermore was very brittle. This was very soon changed to a molybdenum boat filament, which in contrast was clean and pliable.

The prepared base with an 8.3 μ crystal glued in place was fitted on to the top cap brass sheet and a piece of In wire, cleaned by scraping, was put in the cup of the filament. The top cap was placed over the cylinder and the glass dome of the work chamber was lowered into position. The vessel was evacuated to a pressure of just less than 10⁻⁴ mm of Hg. When this pressure was reached, the filament was heated by passing approximately 30A. The metal first melted into a spherical ball and then spread out over the filament. This current was maintained until all the metal had evaporated off the filament, which could be seen through a slit in the cylinder. The chamber pressure was increased to atmospheric and the valve base examined. The In had covered the rectangular area exposed and the crystal was connected via a continuous metallic film up the chamfer of the central hole to pins 1 and 6. The chamber was loaded with silver and the valve base placed on the top cap with the flat face downwards and the pins up in the air. This time it was not located firmly by the pins sticking through the metal but just rested on the top cap so that the rectangular area joined pins 4, 9. The chamber was evacuated and the silver evaporated as before.

The completed diode was plugged in a 9-pin valve socket and examined on the "Tektronix" transistor-curve tracer. This instrument subjects the diode to a rectified sine wave voltage which is continuously monitored on the x-plates of an oscilloscope. The current drawn by the diode is continuously monitored on the y-axis of the
Thus, the instrument traces the voltage/current characteristic of the diode on calibrated scales. The characteristic for reverse voltages is also available. When this first diode (A) was tested it had a square law characteristic but the current was small and the threshold voltage was of the order of 1.5V. The current in the reverse direction was less than in the forward.

For the second diode (B), a 7.6μ crystal was fixed to a base using araldite as before. In an attempt to get better contacts, it was thought that more diffusion of the In into the crystal should help. The base and crystal were placed on a soldering iron at a temperature of 280°C. A small piece of indium was placed on the heated crystal and the base was removed from the heat after a few seconds. After cooling, the base was vacuum coated with indium for the cathode and silver for the anode in exactly the same way as diode A. When tested on the curve tracer, this diode had the turn-over point at ~1.5V and current was small. Then, when a current of ~1.3 mA had been reached, there was a sudden shift on to another characteristic. This had its turn-over point about 3V and it passed 8 mA at 4.7V. This sudden increase in current could well have been too much for the diode, but it was protected from the excessive current by a series limiting resistor. The reverse current of this diode was < 0.003 mA at -50V.

It is probably relevant here to note that this spontaneous shift of characteristic was noticed in several subsequent diodes. When a certain voltage was reached, the current suddenly increased and the voltage/current curve was different from the initially observed one. This shift is in no sense due to the increase in current at a trap-filled voltage limit, since the voltage drops at the same time as the...
current rises, showing that the diode impedance has changed. Further, the initial characteristic can never again be repeated. It was thought that the effect must be something in the nature of a "breakdown", probably of some cathode contact resistance. This same effect has been observed by Alfrey & Cooke \(^{(14)}\). They observed that evaporated or pressed contacts of indium, gallium or aluminium on to crystals of ZnS were markedly non-ohmic, but could be made ohmic by increasing the applied field until a "breakdown" was initiated. They observed also that the electrode could be removed and replaced by any other metal to furnish an ohmic contact, provided that the crystal surface had not been ground in the interim. The inference from this evidence is that when sufficient field is applied, the formation of donor centres is facilitated in the crystal surface, after which ohmic behaviour might be expected.

Diode C. was made by fixing a crystal to the base as before and coating the cathode side of the crystal. The base was then removed from the vacuum coating apparatus and placed on the soldering iron for 60 secs. When the base had cooled, the anode was silver coated. The diode was tested on the curve tracer and it was found that the characteristic would not settle. It jumped continuously from one characteristic to another. This effect had been observed to a lesser extent in diode B, after the "breakdown". The diode C. was heated for a further 60 secs and this helped slightly in steadying the characteristic. However, more heating was tried and this time the diode broke under test. It went short circuit, which may imply that the crystal had cracked from excessive heat or that the current surge at "breakdown" - if this occurred - had been too great.
When diode D was made, the base with an 8.3μ crystal attached was cleaned in carbon tetrachloride before coating. After the dry base had been coated with indium for the cathode, it was placed on the soldering iron for 60 secs as had been done with diode C. The anode was coated with silver as before and the diode tested. Although the current was small the characteristic was very much steadier than before, and the rectification was relatively good. The forward characteristic measured by a d.c. method is shown in graph I. At 16V applied voltage the diode broke, going short circuit. Since the mechanism of the "breakdown" had not been fully appreciated at this time, there was no current limiting resistor in series with the diode for the d.c. measurements. It is, therefore, almost certain that this diode broke as a result of the excessive current flowing when "breakdown" occurred. It can be seen from the dotted curve on graph I that no square law applies in this case, which is further confirmation that the cathode contact was non ohmic.

The diode E used a 5μ crystal and the diode construction followed the method of D, except that this time the crystal was not cleaned in C Cl4. When tested, the current started to flow at 4V and at about 0.1 mA there was a spontaneous jump to another characteristic. In the new mode, current started to flow at 1.5V, but the characteristic was unsteady. The rectification was good—less than 0.002 mA current flowed for -20V.

At this time an improved masking system was made for the diodes. This was part of a plan to coat both anode and cathode without opening the work chamber between coatings. Two masks were made of the shape shown in Fig. 3.2.
The diode was sandwiched between these masks and fixed in a cylindrical clamp arrangement as in Fig. 3.3. The base was located in the cathode mask and the anode mask was fixed relative to this by the small lugs on it.

This cylindrical clamp could be swung along a horizontal arc by a mechanism controllable from outside the work chamber. However, this part of the mechanism was not used immediately. The clamp was positioned all the time over the brass cylinder that surrounded the filament low tension terminal. Used in this way, the new system was merely
a more robust version of the original brass sheet arrangement.

The first diode made using the new masks was diode F. For this diode, a 16.3μ crystal was given two washings in CCl₄ and was stuck on to a cleaned valve base, taking care not to dirty the crystal. After stoving, the valve base with crystal firmly attached was fitted into the clamp arrangement. When the filament had been loaded with the indium metal, the clamp was positioned over it. After evacuation, the low tension current was passed but the current was not switched off immediately the metal had evaporated. The filament was kept hot (at 30A) for a further half minute. After this heating period, the chamber was reduced to atmospheric pressure and the clamp was inverted so as to expose the anode side to the filament. The anode material this time was gold and this was evaporated using the same filament current. When this diode (F) was tested, it was found to be open circuit and this appeared to be due to cathode discontinuity at the join of the crystal and base caused by a sharp edge at the chamfering. A second coating of the cathode was made to try and bridge the discontinuity - using no extra heating this time. The diode was successful. Its current/voltage characteristic using pins 1,9 is shown in graph II(a), which was taken from the curve tracer. The current was very steady and followed a square law as seen from the graph III(a). However, after using this diode for some time, it was found that the characteristic had deteriorated and now followed the graph II(b). The current/voltage relationship was no longer a square law one as can be seen from graph III(b). A later measurement of the characteristic showed that it had changed again - this time to graph II(c). The graph III(c) shows that this is not a square law.
either. Examination of the diode F showed that blackening had appeared at the join of the crystal and base, at the place where there had been discontinuity before. This indicated that the contact to the metal cathode was resistive. Such a resistive element would change the proportional law of $V = c\sqrt{i}$, where $c$ is a constant, to one of the nature $V = Ri + c\sqrt{i}$ i.e. $V = R(i^2)^{1/2} + c(i^{1/2})$. In fact, the curvature of graphs III(b), (c) agree with such a law. Assuming that for graph III(a), there is no resistive element i.e. $R = 0$, then $C \approx 1.4$. Using this in the full equation applied to (b) a value for $R$ is obtained using the values for $V$ and $i_0$ at point B. This gives $R \approx 1.7k\Omega$ and this is reasonably consistent along the graph. Considering curve III(c) at point C the value of $R$ obtained is $3.7k\Omega$ and again this is reasonably consistent along the curve. Thus, the evidence agrees with the idea that the cathode connection was becoming increasingly resistive with time and in fact the diode went open circuit after a while.

The method of constructing diode F was repeated for diode G. A 6.6 μ crystal was cleaned in CC1 and attached to a base. The cathode was coated and additional heat applied for $\frac{1}{3}$ min. Then the anode was coated. When tested, the characteristic was not steady at all, but the diode gave the very large current of 50 mA for $2V$ in the forward direction. Despite this large forward current, the reverse current was very small, 0.04 mA at $-18V$.

Diode H used a 6.6 μ crystal also and was constructed exactly the same as above. Again the current was not steady. 10 mA passed at $8V$ and the current started to flow about $2V$. Reverse current was
Graph IV(c) (diode I)

Measured by a d.c. method.
Graph IV (d) (diode Z)

Log plot of graph IV (b)
Slope $n = 2 < B$
small, 0.01 mA at -10V. Although the diodes G, H were made in the same way as F, they were not so successful in that their characteristics were not steady. Both G, H were thinner than F, but this did not seem a very good reason for the difference in performance. However, it was noticed that the crystal of diode H was only just big enough to cover the central hole in the valve base. As a result, the crystal had been strained into a slightly arched condition by the hardening of the araldite. In diode F, the crystal more than covered the hole and as a result was unstrained. All future diodes were made using crystals quite a bit larger than the central hole of the valve base.

Another diode made by the above method was diode I, using a 10μ crystal. It was a good diode in that the characteristic was perfectly steady and this appeared to verify the idea that the crystal should amply cover the hole in the base. However, the diode was different in that it had an open characteristic, as seen from graph IV(a), and furthermore the characteristic depended to a certain extent on the peak current reached. Graph IV(a) shows the characteristic for a maximum current of 5 mA, which was reached at 11.5V. When the characteristic was examined some weeks later, it had much the same shape but 5 mA current was reached at 7 volts. When it was measured later still, the characteristic had changed its shape completely and followed the curve of graph IV(b). In all cases, the reverse current was small ~ 1 mA at -16V. Each change of characteristic occurred after the diode had been taken up to a high voltage say of the order of 20V and with each change the
Graph $V(a)$ (diode 3)

Slope of $S(a) = 0.66 \, \Omega$
Graph $V(t)$ (Cradle J)

Slope $n = 0.5$
characteristic was improved in the sense that more current flowed at a particular voltage. It was felt that this must be due to the higher applied voltage establishing better cathode contact in a similar manner to the "breakdown" mechanism mentioned before. The openness of the characteristic, as seen on the curve tracer, indicated that the crystal contained trapping centres. These tended to fill on the increasing voltage cycle and empty on the decreasing cycle. As a result the current flowing on the increasing voltage cycle was less than that on the decreasing cycle. Further, graph IV(b) shows a sudden increase in current around $4\frac{1}{2}V$ on the increasing voltage cycle that could well be due to a traps-filled voltage limit.

Measurement of the characteristic by a d.c. method showed this same sudden increase of current. As seen in graph IV(c), the current starts increasing rapidly around $5\frac{1}{4}V$ which agrees with the curve-tracer measurement. A value of $4\frac{1}{2}V$ for the traps-filled voltage indicates a density of traps of $5 \times 10^{19}$ /m$^3$ from equation (2-15), which is quite a plausible value.

Using another 10μ crystal, diode J was made following the same method as above i.e. the method used firstly on diode F. Care was taken that the crystal was large enough to amply cover the base hole. The diode proved to be successful and the characteristic was very steady. No opening out of the characteristic was observed as there was for diode I. The rectification was very good, < 0.001mA at -25V. Graph V(a) shows the characteristic of diode J as taken from the curve tracer. For interest, it was decided to find whether this curve followed any law of the type current = (voltage)$^n$. If this is so, then a straight line graph should appear when log current is
Graph \( V(t) \) (Kohle 4.81)

Slope of 0.3 mA = 10 V \( t \)

--- mag characteristic
Graph VI (b) (decade log)

Slope $n = 2.36$
plotted against log voltage and n will be the slope of this line. When these quantities were plotted for diode J, a straight line was obtained as seen in graph V(b) and the value of n = 7.5. The fact that the index of the power may differ from 2 has been observed experimentally by Bell. Using cadmium sulphide crystals with evaporated indium cathodes and silver in toluene paste for the anodes, he obtained values of n ranging between 1.5 and 3.0. Rose has shown theoretically that, although a crystal containing shallow traps follows a law $I \propto V^2$, this is not true for traps having a distribution of energies. He showed that for a uniform distribution of trap energies below the conduction band, $I \propto V \cdot e^{-V}$. However, the exponential factor is due to the uniformity of the distribution. For a distribution that decreases with distance from the conduction band, the exponential is replaced by a high power function of the voltage, so that $I \propto V^n$ where $n \geq 2$.

Again using the method of diode F, a 23μ crystal was used in the construction of diode K. There was a slight difference in the method in that the scraped indium and gold were washed in CCl$_4$ to remove any residual grease. When tested, the diode had a steady characteristic in the sense that there were no violent fluctuations. However, when 18V applied potential had been passed, the current started to increase with time. This tendency was checked to begin with as it was feared the current would become too great. Thus, the characteristic shown in graph VI(a) is for voltages under 18V. As graph VI(b) shows the diode K does not follow a law $I \propto V^2$ over the whole of its range, but in the range 13 - 18 volts such a law holds approximately with $n = 2.86$. When these measurements and some others had been taken, the diode was subjected to a steady potential of just
Graph VII(a). (mode L)

Reverse

Forward

Volts
Graph VII (b) (doode h)

Log plot of reverse current

Slope = 1.75
more than 18V and the current started to increase with time. As feared, the current kept increasing until it became too much for the diode and the diode broke down and went short circuit.

Although the complete evaporation apparatus had not been installed, it was possible to move the valve base in an arc so that it could be moved clear of any obstructions. It was therefore possible to use ion bombardment for cleaning purposes. The uncoated valve base with a 6.6μ crystal attached was placed in its holder and this was positioned clear of other objects in the chamber. A controlled amount of air was allowed in and an a.c. potential of approx. 3000V was applied via electrodes across the chamber. A steady discharge could be maintained so that the crystal was continuously bombarded with ion particles. Such a discharge prepares the crystal by removing occluded gas, water films and grease films from the crystal surface. For this diode (L), the bombardment was maintained for 10 mins. The long time taken by the pump to evacuate the chamber after this, showed that the pump oil had been contaminated as a result of the by-products produced by the bombardment. The ion bombardment had obviously done its purpose. The cylindrical clamp was swung over the brass cylinder containing the heating filament and the cathode was coated. As before the filament was kept hot for 60 secs after the metal had evaporated to encourage diffusion. The chamber was opened up, the clamp inverted and the anode coated with gold as before. The graph VII(a) shows the current/voltage relationship of this diode for which the forward current is considerably less than the reverse. Neither the forward nor the reverse characteristic appears to have a good square law. However, the log plot of the reverse current in graph VII(b) shows
Graph VIII(b) (diode M)
Graph VIII (b) (d) (dust F1)

(d) from c.c. measurement
(b) from L.c. measurement

Slope of (d) n = 2.2
Graph VIII (c). [diode M]

Measured by a die method.
Graph IX (b) (diode 11)

Log plot of reverse current

Slope: \( n = 2.5 \)
that a law \( I \propto V^n \) is followed approximately where \( n = 1.75 \). The forward current appears to vary linearly with voltage after about 2V. This diode's performance differs so much from previous diodes, particularly with respect to rectification, that the change must be regarded as mainly due to the ion bombardment with perhaps the heating time as another factor.

The next diode (N) was made from a 6.6 \( \mu \) crystal of the same batch as L and in this case ionic cleaning time was reduced to 2 mins and no extra heating was applied to the cathode. As can be seen from graph VIII(a), the characteristic was much improved on that of the previous diode. Although it could not be described as a very good rectifier, the forward current is greater than the reverse by at least a factor of six at 0.5V. It should be noted that the current is very large for such a low voltage. When log current is plotted against log voltage for the current and voltage values of graph VIII(a) then it can be seen from graph VIII(b) that a linear relationship does not hold at least up to 5 mA current. However, when the diode was taken to higher currents, a square law did hold. Graph VIII(c) shows the voltage/current plot of diode M taken by d.c. measurement rather than the signal tracer and graph VIII(d) shows the log plot of these results. From this it can be seen that after about 0.55V the slope gets less and the curve becomes linear with a slope of 2.2.

The third diode made using ion bombardment was diode N, again using a 6.6\( \mu \) crystal. The crystal was bombarded for 2 mins. and the cathode was coated with no extra heating. As seen in graph IX(a), this diode exhibits the same property as L, namely the reverse current is greater than the forward. Moreover, as with L, the
Reverse current follows a law of the type $I \sim V^n$ where $n = 2.38$ from graph IX(b) whereas the forward current follows an approximately linear law.

Out of these last three diodes, $(L, H_1, H_2)$, only one was reasonably successful in the normal sense of the word. Both $L$ and $H$ conducted better in the reverse direction and what is more important they followed approximate square laws only in the reverse direction. In these two diodes the roles of anode and cathode appear to have been reversed, since the forward current follows an approximate resistive law as would be expected from a blocking contact. The reverse current follows the law one expects from an ohmic contact. The only way to explain this is to assume that the contact made with indium has been bad i.e. resistive and that the contact made with gold has been contaminated with indium. It is self-evident that the use of ion bombardment is a direct or indirect cause of this behaviour because the use of bombardment is the main difference between the construction of these diodes and previous ones. Because both anode and cathode were coated from the same filament, it was a possibility that some indium that had been left on the filament after coating the cathode, was evaporated along with the gold when the anode was coated. However, the most likely source of the indium was not from the filament itself but from the sides of the cylinder surrounding the filament. After several evaporations, a considerable coating of indium (and gold) had built up on the sides of the cylinder. Under the action of the filament heat, this indium could possibly be re-evaporated along with the gold during the anode coating. This could of course have happened previous to ion bombardment, but with
Graph N(l, cone 0) : 
- mag characteristic
- Step of Ind. = 340 x
Graph X (SI) (Cdo So C)

Slopes = 2.59 ± 1.87
Graph X(t) (diode D)
a very clean crystal surface a small quantity of indium would be much more effective. Such an effect would readily explain the large square law current in the reverse direction, but would make one expect a symmetrical diode with equal current in either direction. It does not explain why a poor cathode contact was made.

Another diode was tried, this time using a 13.3 μ crystal. Ion bombardment was employed for 2 min. and then the cathode was coated. The anode was coated slowly without using more heat than necessary so that indium would not be re-evaporated off the cylinder. When first tested, diode 0 passed low current for high voltage, but it then suffered a "breakdown" as had occurred with previous diodes. After that, the diode showed quite a good characteristic, graph X(a), although it did not rectify particularly well. The current ratio was only 8:1 at 5 volts, which is about the same as diode M. Up to 5 mA current, graph X(b) shows that the current follows an $I \approx V^2$ law w.r.t. voltage for a value $n = 2.67$. When the range of values was extended (Graph X(c)), it was found that beyond the 5 mA point, the law changed to a value $n = 1.67$. This is similar to diode M where the law also changed around 5 mA current.

Two further diodes were made, which, although they had poor characteristics, are worth reporting. The first was made using 2 min of ion bombardment as before, but the gold anode was coated before the indium cathode. This diode conducted as much current in the reverse direction as in the forward, indicating that the anode had been polluted with indium. Immediately prior to the anode coating of this diode, the filament had been used in coating the anode of diode 0, a successful diode. Thus, the indium pollution of the anode in this case
could not have come from the filament. This indicates that indium must be re-evaporated from the cylinder walls under the action of filament heat, and that this is the source of the pollution. The other diode of interest is one where no ion bombardment was used at all. This diode was similar to previous types in that the characteristic jumped continuously from one characteristic to another. The important thing, however, was that it rectified very well, which none of the diodes made using bombardment had done. This confirms the view that the bombardment is responsible at least indirectly, for the poor rectification of the last few diodes.

It had always been the intention to coat both anode and cathode in a continuous operation not requiring the chamber reduced to atmospheric pressure throughout. This would not only speed up the whole operation but would also reduce the possibilities of contamination. Previously, part of the apparatus had been installed. The prepared valve base was held in a cylindrical clamp which kept the masks in position. This clamp, which was shown in Fig. 3, could be swung along a horizontal arc by an operation performed outside the evacuated vessel. In this way, it could be positioned either over the original brass cylinder surrounding a low tension electrode or under an additional cylinder by swinging it along the arc. The new cylinder contained another filament which was connected to a low tension electrode. The two electrodes could be activated separately. Since the evaporation of the metal was to take place downwards onto the valve base, a molybdenum boat filament could not be used. This filament would cast a shadow and evaporation would only take place in the upper hemisphere. Thus, despite its dirtiness and brittleness, a tungsten helix filament was fitted. In use a loop of the metal was
placed on the filament. The filament was heated gently at first so that the metal melted and then clung to the filament by surface tension. After that the filament was heated to full heat and the metal evaporated. Because each filament and cylinder deals with its own metal now, there is little risk of the anode becoming contaminated with indium. Further, because ion bombardment plays such an important role in the kind of diode produced, the time for which bombardment proceeds was reduced. Diode P was made from a 6.6μ crystal and the crystal was bombarded for \( \frac{3}{2} \) min. only. The anode was coated first and then the cathode without the chamber being opened to the atmosphere. When tested, the characteristic was poor, low current for high voltage. However, at sufficiently high voltage a "breakdown" occurred and the characteristic became good as shown in graph XI(a). The forward characteristic follows a very good square law characteristic after 2 volts, as can be seen from graph XI(b). The reverse current is very low resulting in a good rectification ratio.

The above method having been so successful once was repeated for another 6.6μ crystal. This diode exhibited a "breakdown" but even after this the diode was poor. The rectification ratio was only 5:2. The only apparent difference in the construction of diode P and this diode was that in the case of P the crystal was allowed to stand some considerable time after the bombardment had been completed before the coating was done. For this diode, the coating was done immediately after bombardment.

This method was tried again. Using a 6.6μ crystal, the valve base with crystal was bombarded for \( \frac{3}{2} \) min and then allowed to stand for
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<td>non-characteristic</td>
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**Diagram:**

- A steep, ascending line indicating a trend or relationship.

**Note:** The data points or specific values are not clearly visible in the image.
Graph XII(b) (Node G)

Slope n = 0.8
1½ hours before the anode and cathode coatings were put on. Once again for this diode (q), a "breakdown" occurred at high enough voltage and this time the characteristic was good afterwards. The voltage current characteristic is shown in graph XII(a). The rectification ratio is better than 50:1 at 2½V. The forward current follows a law of the type \( I \propto V^n \) where \( n = 4.2 \) as can be seen from graph XII(b).

This diode and diode p were both good rectifiers and in both cases the crystal was allowed to stand for some time after bombardment before the coating was done. On the other hand, the diode which was coated immediately after bombardment, was a very poor rectifier. At first sight it would appear that there was some significance in a lapse of time between bombardment and coating. However, the following diode (R) turns out to be a poor rectifier and the crystal stood several hours between bombardment and coating.

Diode R was a double diode. Because it has been so difficult to get consistent characteristics from the various diodes made so far, it would obviously be of interest to try to cut down the number of ways in which the diodes can differ. For example, if two diodes were made having the same crystalline insulator and the same cathode but having different thicknesses and different anodes, then it would be much easier to analyse the differences in their characteristics. For this reason and for reasons connected with the noise measurements to be discussed later, it was decided to make such a diode. The first necessity was to make a crystal having two different thicknesses - that is a crystal of the shape shown in Fig. 3.4.
With present techniques, it seemed too difficult to try to grow the crystal in such a shape, so attempts were made at etching. It was found that conc. HCl dissolved CdS readily and that the crystals could be protected from the action of the acid by coating the surface with paraffin wax. The system was to protect one half of the crystal with wax and to etch the other half with HCl for a definite period of time. Using a glass slide as a base a layer of paraffin wax was spread on the glass. This was done by melting the wax with a very small quantity of benzene in a test-tube and painting the solution on to the glass with a small brush. It solidified on the glass in a matter of seconds. A 10µ crystal ~4 sq.mm. in area, relatively free from striations and cleaned in CCl₄ was placed on the base of paraffin wax. Approximately one half of the crystal was covered with wax deposited in the above manner and wax was sealed round all the edges so as to prevent the acid seeping under the crystal. This work was conducted under a stereo microscope. When the wax had set hard, a drop of conc. HCl was placed on the exposed half of the crystal and the reaction was stopped by sweeping the acid away with a jet of water. The wet crystal was dried using alcohol. The block of wax containing the crystal was cut out from the rest of the wax and placed in a test tube with benzene. In order to dissolve the wax off the crystal, the benzene had to be heated to nearly boiling point. However, it could
not be boiled since the violent action of boiling would break up the crystal. The method used was to heat the test tube of benzene in a beaker of boiling carbon tetrachloride. The \( \text{CCl}_4 \) boils at 76.8°c, whereas the benzene does not boil until 80°c. By this method the benzene could be heated to just less than its boiling point where it readily dissolved the wax. It should be noted that only very small quantities of \( \text{CCl}_4 \) were boiled, since in the presence of an open flame, it gives rise to dangerously acidic gases. The crystal was removed from the benzene and given several washings in \( \text{CCl}_4 \). After this it was examined under the microscope. When examined edge on, it was found that 15 seconds of etching had reduced the thickness from 10μ to 6.6μ. The etched surface could not be described as smooth, but was smooth over relatively large areas. The flatness of the surface was spoiled by several small peaks sticking perhaps a micron above the general level. However, these were small in area compared with the flat areas so they could have little effect on the behaviour of any diode made from this crystal.

The double thickness crystal was cleaned again in \( \text{CCl}_4 \) and then was stuck on to a valve base so that the line separating the two thicknesses was centrally placed relative to the hole in the valve base (see Fig. 3.5). Although the cathode is to be common to both diodes, the current falls off as the distance cubed so that each anode will deal effectively with that part of the cathode immediately below it. Thus, if a comparison is to be fair, then the effective cathode areas should be equal in each case. When the araldite had been cured, the next stage of the operation was attempted. It was required that
gold should not be deposited along the line separating the two thicknesses. The original anode mask as shown in Fig. 3.2 consisted of a cross formation, the outline of which is shown in Fig. 3.5.

![Diagram](image)

**Fig. 3.5.**

It was necessary to divide this cross shape into two parts, each dealing with one half of the crystal. However, when in use, the mask did not fit very close to the crystal, so that any dividing wire, fitted to the mask itself, would not cast a sharp narrow shadow as was required. Instead of altering the mask itself, a thin wire of 40 gauge diameter was placed along the line separating the two thicknesses and was stuck on the valve base itself in the position marked "X". The wire was in close contact with the crystal and so it threw a sharp shadow. The crystal was bombarded and left overnight before the anode and cathode were coated in the usual manner. The wire was removed and the line of separation accentuated by scraping gently so that the two anodes were separated electrically. The 10μ section was tested first. It passed low current for high voltage to start with but the characteristic became good after sufficiently high volts had been applied and a "breakdown" was initiated. The 6.5μ section behavied
Graph III. (c) (d) (double diode 2)

(c) \( V \eta = \text{Slope} \eta \approx 0.6 \)

(d) \( \eta \rho = \text{Slope} \eta \approx 2.47 \)
similarly and suffered a "breakdown", but it was noticed that at equal voltages, the thinner crystal was giving less current than the thicker, which is contrary to theoretical prediction. However, when the 6.6μ section was subjected to a higher voltage still, the characteristic jumped again due to another "breakdown", after which the 6.6μ section carried more current than the 10μ section at equal voltages, as would be expected. Now if, as has been supposed previously, these "breakdowns" are the result of the formation of donor centres in the crystal by the diffusion of In atoms, then at first one would not expect the second diode to exhibit a "breakdown" after the first had done so. This is because donor centres would have already been formed. However, further consideration shows that during the first "breakdown", donor centres would only be formed under the area of the 10μ section anode. With a voltage applied across the 6.6μ section, the effective distance between these donor centres and its anode would be very much greater than 6.6μ and further the effective area would be very much less than in the 10μ section case. Thus, it would be expected that the current should be small initially. When a sufficiently high voltage was reached, a "breakdown" would be expected producing donor centres under the area of the 6.6μ section anode. The first "breakdown" of the 6.6μ section was probably due to donor centres being formed near the original ones and the second "breakdown" would be due to their formation over the rest of the area. The final current/voltage plots of the two sections are shown in graphs XIII(a), (b). From these graphs, the ratio of currents at 1.45V is seen to be 5:1.75 or 2.86:1. The inverse ratio of thicknesses is 10.6.6 or 1.52:1. When
cubed this ratio is \( \sqrt[3]{3.48} \). From theoretical considerations, the current should be inversely proportional to the cube of the crystal thickness. The agreement of diode \( R \) with this theory is not very good. Graphs XIII(c) (d) show the log plots of current vs. voltage from which it is seen that the 10\( \mu \) section follows a law \( I \propto \sqrt{V} \) and the 6.6\( \mu \) section follows a law \( I \propto V^{2.15} \). The fact that the two diodes follow different laws does not explain the discrepancy between the current ratio and the inverse cube of thickness ratio. In fact when the different laws are taken into account the current ratio is decreased making the agreement between practice and theory poorer. The true reason for the discrepancy is probably that the two diodes are not in fact using the same cathode. As mentioned previously, each anode deals effectively with the section of the cathode beneath it. Differences in the donor centre distribution would make the effective cathodes different and so make the comparison an unfair one. Because the same type of crystal is used reasonable agreement between practice and theory would be expected and this is obtained. Graphs XIII(a) (b) show poor rectification for both sections of diode \( R \) and this fact dispels any idea that the time delay between bombardment and coating has a bearing on the rectification properties of the diodes. For this double diode, a period of several hours elapsed between bombardment and coating. In previous diodes such a lapse of time had produced good rectifiers but not this time. Poor rectification is still unexplained therefore.

The diodes made so far have been tested for forward and reverse current/voltage characteristics and were further tested to see whether they followed a law of the type \( I \propto V^N \). These general characteristics have been established but further information, namely diode a.c.
resistance and capacitance would not only be of general interest but would also be useful when the diodes came to be used as noise sources. Thus, it was decided to measure these quantities at 20 Mc/s, which is the noise frequency to be considered and further to take the measurements while d.c. bias was applied to the diodes. The measuring device was to be a 20 Mc/s bridge of the Wen type but it was to measure changes in value rather than absolute value. Measuring changes in value is the easier method at 20 Mc/s since stray capacitances can be large at this frequency and would make any measurement of absolute value very difficult. It was intended initially to measure only the capacitance of the diodes but it was found that the bridge could measure a resistor and capacitance in parallel so that both the a.c. resistance and capacitance of the diodes could be measured. The circuit of the bridge is shown in Fig. 3.6. It was powered from an Advance E2 signal generator used on full power, giving a modulated 20 Mc/s signal. The basic bridge consisted of two 100Ω resistors and two 100 pF capacitors in a Wen bridge formation and this could be balanced by the 10 kΩ slider resistor. When balanced, the unknown capacitance and resistance of the diode were placed in parallel with one of the 100 pF capacitors. This change could then be balanced out by a variable resistor and capacitor in parallel with the other 100 pF condenser.
The bridge included blocking condensers to isolate the d.c. bias voltage from the bridge and also RF coils to isolate the power supply from the 20 Mc/s. A B9A valve base socket was fitted to take the diode under test. The variable resistor and capacitor were mounted on a plug-in unit and were wired so that they were in parallel only when plugged into the bridge. Otherwise they were unconnected electrically.

The variable resistance was a non-inductive carbon slider of value 27kΩ. This is a large value to balance against an expected a.c. resistance of the order of 500Ω, but smaller values of these carbon sliders could not be obtained. Despite the large value, the resistor was variable down to 100Ω. The variable capacitor was the beehive type variable between 4 pF and 50 pF. In use, the bridge was first balanced without the diode or the variable plug-in unit in position. However, the biasing power supply was connected, although passing no current.

The detector used for balancing the bridge was a Solartron oscilloscope with a germanium diode in series with the input. The oscilloscope was used at its greatest amplification of 1 mV/cm. The diode rectified the out of balance RF current and the oscilloscope...
showed the modulation wave. A sharp balance could be obtained by varying the 10 kΩ slider resistor. When the bridge was balanced, the diode and variable plug-in unit were fitted and a new balance obtained by varying the resistance and capacitance of the plug-in unit. The plug-in unit was then removed and the value of the resistance measured on a Marconi Impedance Bridge. The capacitance was measured on a Marconi Circuit Magnification Meter. This apparatus uses a tuned circuit at 20 Mc/s. A small additional capacitance in parallel with the circuit can be balanced out by reducing the variable capacitance of the circuit so as to retune the circuit. The value of the additional capacitance will equal this change, which can be read off the scale. The resistor could not be in parallel with the capacitance during this measurement since this would damp the tuned circuit and a maximum reading would not be obtainable. This is why the diode capacitance could not be measured directly on the magnification meter.

The bridge circuit was first tested on known values of capacitance and resistance. Two mock-diodes were made up. Using a B9A valve base from which the soft leads had not been removed, a 5 pF condenser and a 470 kΩ resistor were soldered in parallel across pins 1, 9. A second diode simulator was made using a 10 pF condenser and a 330 kΩ resistor. These two mock-diodes were tested on the bridge. The values obtained from bridge measurement were within 10% of the actual values. Having shown the bridge capable of reasonably accurate measurement, some actual diodes were tested. Diode F was tested at various biasing currents. A table of the results follows:
The steady increase in resistance with decrease of bias current agrees with the variation of the slope of graph II(a). However, the measured values do not all agree with the slopes within the accuracy of 10%. This is probably partly due to the fact that graph II(a) is traced at 100 c/s whereas the bias currents are stationary. The d.c. current/voltage plot is never exactly the same as the curve-tracer plot, so that the slope corresponding to a steady bias point would not necessarily be the same as at a transient bias point. Furthermore, since it is the incremental values of resistance and capacitance that are required, the measuring signal should not be too large, otherwise the bias point may move appreciably relative to the no-signal bias point. The fact that, in certain cases, the measured results of resistance agree so well with the graph slopes, indicates that this source of inaccuracy must be small. The last value of capacitance differs from the others, but this does not imply a sudden change, only that there has been an increase. The accuracy of the capacitance measurement is limited by the sharpness of the balance point so that there could be a gradual increase as the bias current was reduced. However, it is certain that there was an increase in capacitance as the bias dropped from 5 mA to 1 mA. It is of interest to compare the measured value of capacitance with the theoretical value. It has been shown (16) for a.c.c. condition, where a square law is followed, that the theoretical value of capacitance is

$$C = \frac{7 \times 10^{-6}}{2\pi d^2}$$

where A is the area and d the thickness of the dielectric material. For Diode 1,

$$A = 16.7 \times 10^{-6} \text{ sq.m.}$$

Assuming the dielectric constant for calcium sulphide to be 10, this gives

$$C = 5.15 \text{ pF}$$

which is quite
Diode I was tested on the bridge, but it proved difficult to keep the bias steady at 5 mA, which was the desired operating point. This fluctuation of the d.c. conditions made it difficult to balance the bridge. However, a balance was obtained and the measured values turned out to be 130Ω and ~50 pF. Although no accurate value can be taken of the slope of graph IV(a), it is certainly of the order of 130Ω so that the resistance measurement agrees at least roughly with the graph slope. The capacitance of ~50 pF is quite huge. This is in all probability not a true capacitance. The unsteadiness of the biasing current shows that there will be a large noise signal. The effect of such a signal at 20 Mc/s appearing in that arm of the bridge could only be minimised by introducing a large capacitance in the other arm so as to reduce the impedance of the path AC3. Thus, the measured value of ~50 pF probably bears no relation to the true capacitance. Certainly the measured value is many times larger than the theoretical value, which for $d = 10 \times 10^{-6}$ m and the cathode area equal to that of F is $C = \frac{36}{5} \mu F$. The feeling that the measured capacitance of diode I was the result of spurious signals was strengthened when diode J was tested on the bridge. A balance proved completely impossible in the case of J because of the random signals. On this occasion the noise could actually be seen on the oscilloscope detector.

For diode K, since the current was not taken up as far as 5 mA, the d.c. bias was chosen as 0.3 mA. The capacitance was measured as 8.2 pF and the a.c. resistance as 2 kΩ. The measured resistance value does not agree at all with the slope of the graph VI(a) which is 18 kΩ. However, this is not surprising since the bridge was not
designed to deal with such large values of resistance. The measured capacitance is quite a bit larger than the theoretical value, which for the $23\mu$ crystal, assuming the same area as before, is $2.25\text{pF}$.

The next diode to be tested on the bridge was $0.0000$ biased at $5\text{mA}$ current, the measured value of capacitance was $11\text{pF}$ and the a.c. resistance was $320\Omega$. The slope of graph $X(a)$ was $340\Omega$ which agrees very well with the measured value. The theoretical capacitance for the $13.3\mu$ crystal was $3.9\text{pF}$, again assuming the same cathode area as before. The theoretical capacitance is again less than the measured value.

For diode P, the slope of graph $XII(a)$ is $330\Omega$ and the bridge measurement gives $330\Omega$ also, which is again very good agreement. The theoretical and measured capacitance values do not agree so well. The measured value was $7.7\text{pF}$. The calculated value for the $6.6\mu$ crystal, assuming the usual cathode area, was $7.9\text{pF}$, which is slightly greater than the measured value.

Diode $Q$ at $5\text{mA}$ bias had a bridge a.c. resistance of $150\Omega$ which agrees well with the slope of graph $XII(a)$ i.e. $130\Omega$. The measured capacitance was once more greater than the theoretical value. The measured value was $14.8\text{pF}$ and the calculated value was the same as for diode $P$ (i.e. $7.9\text{pF}$) since the crystals were the same thickness.

The double diode $R$ was also tested on the bridge. The $10\mu$ section was tested first using pins 1,9. The a.c. resistance was $300\Omega$ and the capacitance $4.7\text{pF}$. Graph $XIII(a)$ shows a slope of $580\Omega$ which agrees only moderately well with the measured value. For the $10\mu$ section, for reasons explained before, only half the area of the crystal is operative at one time. Therefore, the calculated
capacitance is 2.6 pF, which does not agree well with the measured value. For the 6.6 μ section the a.c. resistance was measured as 150 Ω using pins 1, 7 and the capacitance as 7.3 pF. The slope of graph XIII(b) is 120 Ω which is in good agreement with the calculated value. The theoretical capacitance is 4.0 pF. It should be noted that for both sections of the double diode, the theoretical capacitance was less than the measured value, but furthermore the ratio of the observed capacitances, 7.3: 4.7 = 1.55:1 is in very good agreement with the inverse thickness ratio 10: 6.6 = 1.52:1.
Conclusion.

Various methods of constructing insulator diodes have been tried and these have been considered in the preceding pages. The earliest diodes showed somewhat variable results. Some only passed low current for high voltage and those that passed large current had poor characteristics in the sense that the currents were not steady. However, they had one thing in common - they were all good rectifiers. An improvement in the steadiness of characteristics was brought about by cleaning the crystal thoroughly in CCl₄ before use. This was done for diode F which was the first really good diode made. In this case, the diffusion of In was aided by using the filament to heat the crystal after the cathode metal had been evaporated. This method was used in the construction of several more diodes - G, H, I, J and K, but did not prove successful in the cases of G, H. Although these diodes passed quite large currents at low voltages, they were not steady. This was possibly due to residual dirt on the crystals but was most probably a result of the crystals being strained. For the diodes I, J, K care was taken that the crystals amply covered the central hole of the valve base and this prevented the araldite from deforming the crystals. As a result these diodes had steady characteristics. I, J passed large currents, but for K the current was small, although it followed an approximate square law. This small current can be partially explained by the thickness of the crystal. The openness of the characteristic of diode I was probably due to the presence of a large number of traps and had nothing to do with the method of construction. The method of construction used first for diode F can therefore be described as a reasonably
successful method. Although good results could not be guaranteed every time, the percentage of successes was high.

Although the previous method had been relatively successful, it was decided to try a new method involving ion bombardment. The first few diodes did not show very consistent results. L and N conducted more current in the reverse direction than in the forward and in each case, the reverse current followed an approximate square law whereas the forward current tended to become linear after a few volts. M and O were more normal in their behaviour — the forward current was greater than the reverse — but they were still poor rectifiers. The reason for such large reverse currents in L, N and for the poor rectification of M, O is certainly bound up with the use of ion bombardment. This is so obviously true because every diode made before the use of ion bombardment was a good rectifier, with reverse current as low as 0.003 mA at -50V. The four diodes L, M, N, O, had large reverse currents because indium polluted the anode material. The indium was re-evaporated off the cylinder walls. This could have happened with previous diodes and probably did. However, the small amounts of In proved very effective in these four cases because ion bombardment had cleaned the surfaces so efficiently. This reasoning readily explains the large reverse currents, but does not explain why the forward current should have been less than the reverse in the cases of L, N. The fact that the forward current in these two diodes tended to be linear indicates that the contacts were poor but no reason for this can be seen except that the surfaces must have been dirty in some way.

The possibility of the anode becoming contaminated in the above manner was reduced by evaporating the different metals within their
own cylinders. This apparently solved the problem, for the first
diode made by this method (P) was very successful and was a good
rectifier. Similarly diode Q was a very good diode. However, diode
R, although a good diode so far as forward characteristic is concerned,
was not a good rectifier, despite the fact that it was made exactly the
same way as P and Q. It is possible that some indium was loaded into
the evacuation chamber along with the gold or that leakage can take
place between cathode and anode through the araldite. However, no
real explanation for the poor rectification of diode R can be given.
The method of construction is reasonably successful since good
steady square law forward characteristics are obtained. However,
the method sometimes produces rather large reverse currents.

During the testing of the earliest diodes, the mechanism of
"breakdown" was first observed. It was observed in several
subsequent diodes, but it was not appreciated until much later that
this was a definite mechanism connected with the formation of donor
centres. The spontaneous jump from a characteristic of low current
at high voltage to one of large current for low voltages was observed
in seven diodes out of the total eighteen constructed.

Most of the diodes were examined to see whether they followed a
law of the type $I \propto V^n$, where the theoretical value of n is two if
shallow traps only are present. Atkinson showed theoretically that
$n$ will take on values differing from two when deep traps are also
present. Since any practical crystal would be expected to contain
traps of all energy levels, then it is not surprising that the
measured values of $n$ differ from two for most of the diodes. In
general, the measured values of $n$ lie in the range 1.5 to 3. However,
$J$ is exceptional in having $n = 7.5$ and $C$ has $n = 4.2$. These results
show that deep traps are present which is as expected. However, it
is extraordinary that values so close to two should have been obtained
in the cases of P and the 6.6μ section of R. It is unlikely that
these values are due to the absence of deep traps and so some
compensation mechanism must apply in these cases. For example, it
could be possible for the crystal to contain a density of donor
impurities. These would readily give up their electrons in order to
fill the deeper lying traps. These filled traps would then play no
part in the behaviour of the crystal and it would thus give the
appearance of being relatively free from deep traps.

When the various diodes were tested on the bridge, it was found
that in general there was reasonable agreement between the measured
a.c. resistance and the slope of the current/voltage graph at the
operating point. The slopes were mostly within 20% of the measured
values. For the 10μ section of diode R, the agreement was poorer than
this and for diode K there was no agreement at all. However, this
latter case is explainable since the bridge was not designed to
measure large resistances. Comparing the measured capacitance with
the calculated values, it appears that in general, the observed value
is larger than the calculated value, by a factor that varies between
1.6 and 3.6. The only exception is diode P where the observed value
is very slightly less than the theoretical value.
CHAPTER IV

Some of the successful insulator diodes were treated as noise sources. Having been fitted in a shielded box of similar construction to that in the Marconi standard noise generator, the noise from each diode was amplified, detected and the output read on a d.c. meter. The standard noise generator was then substituted for the crystal and its output increased until the amplifier output was the same as for the crystal. For equal amplifier outputs, the amplifier inputs may be assumed equal, no matter what the law of the amplifier may be. Therefore, the input voltages to the amplifier may be equated or rather since it is noise signals that are being dealt with, the mean square voltages may be equated. However, although it is true to say that the two inputs to the amplifier are equal, it does not immediately follow that the outputs of the two noise current generators are equal since each feeds into a system with a different impedance. Therefore, the ratio of the mean square currents is not unity but equals some factor $f$ which depends on the impedances of the two systems. Thus,

$$\frac{i^2_{\text{crystal}}}{i^2_{\text{gen.}}} = f \quad \ldots \quad (4-1)$$

or

$$\frac{2 I^2 e I \Delta f}{2 e I_o \Delta f} = f$$

or

$$f^2 = \frac{I_o}{I} \cdot f \quad \ldots \quad (4-2)$$

The value of the factor $f$ can be found for each diode and this will be discussed later. The current $I$ is the direct biasing current through the crystal diode and this is known for any particular measurement. $I_o$ is the d.c. current through the standard noise diode and this can be found from the observed noise factor $F$ by the formula $F = 20I_o R$, where
R is the output impedance of the noise source namely 71 \text{\Omega}. Rewriting equation (4-2), we have

$$R^2 = \frac{F}{1420 I} \cdot f$$

$$= 0.705 \frac{F}{I_{mA}} \cdot f \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4-3)$$

where I now reads milliamperes.

Thus, the method consists basically of comparing the noise from the crystal diode with the noise from a standard source. In order that this comparison should be a fair one, the circuits of the two noise sources should be identical as far as high frequency a.c. signals are concerned and all the shielding precautions taken in one case should be taken in the other. The noise diode of the Marconi noise generator TF 987/1 is housed in a shielded box along with the associated output resistor, blocking condensers, filters, etc. and leads are taken through by means of a coaxial socket and feed-through capacitors. A copy of the shielded box was available from previous experiments and this was used for housing the crystal diodes. The circuit used (Fig. 4.1) was essentially similar to the Marconi one. The a.c. output is taken from the diode in parallel with a 71 \text{\Omega} resistor since the 0.001 \mu F condenser effectively earths one end of the 71 \text{\Omega} resistor. The circuit differs from the Marconi one in that here the HT- is earthed instead of the HT+, but this is merely a matter of convenience and does not alter the a.c. equivalence of the two circuits. As a consequence the filter coil is placed in the HT+ lead instead of the HT- lead. This coil of 1 \mu H in conjunction with
the feed through capacitor of 780 pF is an adequate filter at 20 Mc/s and prevents any 20 Mc/s signal feeding into the shielded box via the HT lead. In addition, the power to the shielded box is carried by a coaxial cable to minimise hand capacitance effects.

![ Circuit Diagram ]

Fig. 4.1.

There are now two similar noise sources, the standard noise generator and the crystal diode noise source. Each is applied in turn to the input of a high gain 20 Mc/s amplifier. This was a two stage amplifier, both sections of which were borrowed from Ferranti Limited, Edinburgh. The main section was a 120 db, 20 Mc/s I.F. amplifier, with an input impedance of 70 ohm. This required two stabilised power supplies one at 200V and the other at 100V. The other section, used as a head amplifier, had a gain of 40 db at a frequency of 20.5 Mc/s. This section required a stabilised power supply of 140V. The output impedance of the head amplifier was 70 ohm.

A frequency of 20 Mc/s was chosen so that low frequency % noise would be negligible and also so that transit time effects could be neglected.
so that it was matched to the input of the main amplifier. The two
sections were tuned to the same frequency (20 Mc/s) using a signal
generator and treating each section on its own. Each gave the
expected gain. The two units were put together and a voltage gain
of approximately $10^8$ was obtained. However, the combined amplifier
exhibited a hand capacitance effect showing that it was not
completely stable. It was thought that some phase adjustment between
the two amplifiers might help. Consequently, the 82 pF condenser on
the grid of the first valve of the main amplifier was increased to
1000 pF. This resulted in a marked improvement and so the same
procedure was carried out on the next valve but one, where 470 pF
was changed to 1000 pF. This produced a degree of stability that
was quite acceptable.

The output section of the main amplifier was a double triode
valve (12AU7). The front section of this valve was used as an
infinite impedance detector and the second triode section acted as
a d.c. amplifier. The output was taken from the anode of the second
triode section. As a result, the detected noise signal would be
obtained but the d.c. anode voltage of the valve would also appear.
To remove this anode voltage from the detection system, the arrangement
of Fig. 4.2 was used. The anode voltage for no input signal
(except the thermal noise signal from input resistance) was balanced
against the variable voltage obtainable from a resistance chain across
the high tension leads. When a signal was applied, the amplified
signal was read on the 50μA range of a Model 8 Avometer.
With reference to equation (4 - 3), a source of inaccuracy in calculating values of $F^2$ is the use of $F$ values in the equation rather than measured values of current $I_0$. The relationship $F = 20I_0R$ has been used but the accuracy of this depends on the accuracy of the makers calibration of the noise generator. It was while extending the range of the generator to give lower noise factors that it was noticed that the overall accuracy of the instrument was poor. The modification itself could have had no effect on accuracy since it only involved inserting a resistor in the heater circuit so that lower emission could be obtained. The inaccuracy of the instrument was typically of the order of 10%, but was sometimes as great as 30% at the low end of the scale. For example, when the noise factor meter read 2, the actual current through the noise diode measured by an Avo
was 1.58 mA and this meant the noise factor should have been
F = 20 x 71 x 1.58 x 10^{-3} = 2.24. This inaccuracy was shown to be
due to the noise factor meter shunts and these were replaced by
resistors complying more accurately with the calculated values. The
calibration was examined again and was found to be much improved.
The accuracy was now within 3 or 4 per cent for most ranges and the
poorest was 7% at the low end of the scale.

In equation (4 - 1), the factor f was introduced. This factor
relates the ratio \( \frac{I^2_{\text{crystal}}}{I^2_{\text{gen}}} \) to the equal amplifier input voltages
and the evaluation of this constant must now be discussed. The
input circuits of the noise generator and the crystal diode are shown
in Figs. 4.3(a), (b).

![Diagram](image-url)
The standard noise source may be considered as a pure current source having infinite shunt impedance. The output resistor, which is in parallel with the generator, is a 71Ω resistor. This output is connected via an 80 cm length of 70 Ω coaxial cable to the amplifier input, which has an input impedance of 180Ω with 18 pF in parallel. The crystal diode can be drawn as a pure current generator with the diode a.c. resistance R and capacitance C in parallel with it. This is connected to the amplifier by a 51.5 cm length of 70 Ω coaxial cable and the amplifier has the same input impedance. Now, considering Fig. 4.3(a), we wish to relate $v_1^2$ to $i_1^2$ gen. This can be done using the fact that the power dissipated in the total resistance at one end of the line equals the power dissipated in the total resistance at the other end, assuming a loss free line. In this total resistance is included not only the resistance at one end of the line but also the resistance, as seen at that end, of the impedance at the other end. In other words, it is the resistive components of the total input impedances at either end of the line that are of interest. Thus for Fig. 4.3(a), the total admittance at the amplifier end of the line would be $Y_1 + Y_{3'}$, where $Y_{3'}$ is the admittance of $Y_3'$ transferred along the line to the amplifier end. This admittance $Y_1 + Y_{3'}$ will consist of a conductance component $G_1$ in parallel with a susceptance component. Thus, the power dissipated at the amplifier end would be $v_1^2 G_1$. At the generator end, there will be a total admittance of $Y_3 + Y_{1''}$. This complex admittance can be readily converted to a complex impedance using the Smith Chart and this, in fact, converts a parallel combination of components to a series combination. Therefore, the
current generator can be thought of as feeding into a series combination of resistance and reactance i.e. \( R_3 + jX_3 \) and the power dissipated at this end of the line is \( \overline{I^2} \text{gen.} \ R_3 \). The two powers must be equal and so

\[
\overline{I^2} \text{gen.} \ R_3 = \overline{V_1^2} \ G_1
\]

Similarly for Fig. 4-3(b)

\[
\overline{I^2} \text{crystal} \ R_4 = \overline{V_2^2} \ G_2
\]

Therefore, since \( \overline{V_1^2} = \overline{V_2^2} \) by experiment,

\[
\frac{\overline{I^2} \text{crystal}}{\overline{I^2} \text{gen}} = \frac{R_3 \ G_2}{R_4 \ G_1} \quad \ldots \quad (4-4)
\]

Thus

\[
f = \frac{R_3 \ G_2}{R_4 \ G_1} \quad \ldots \quad (4-5)
\]

from equation (4-1). Since all these values can be found, the values of the factor \( f \) for the various diodes can be calculated. The values of \( G_1 \) and \( R_3 \) for the generator circuit will be the same in all cases, but the values \( G_2 \) and \( R_4 \) will differ from diode to diode because of the different diode impedances. The values of \( f \) for two typical diodes have been given in detail in the Appendix I.

**Experimental noise measurements.**

The first noise measurements obtained were with the diode F, the characteristic of which is shown in graph II(a). The diode was placed in the shielded box and a current of 5 mA was passed through it. The reading on the amplifier output meter was noted. The standard noise source was substituted for the diode and its output increased until the amplifier output was the same as for the crystal. The
noise generator under these circumstances read 1.0 which is the noise factor. Now for the diode F, biased at 5 mA, it has been shown that the diode resistance $R = 340 \Omega$ and the diode capacitance at 20 MHz $C = 5 \text{ pF}$. Using these values to evaluate the factor $f$, Appendix I shows that $f = 1.25$ for diode F. Thus, using equation (4-3),

$$r^2 = 0.705 \times \frac{1.0}{5} \times 1.25$$

$$= 0.18$$

This shows that the noise produced by the diode F at 5 mA bias is less than the full shot noise at 5 mA by a factor of 0.18 which is a considerable reduction.

At the same time diode I was tested, again using 5 mA biasing current and on this occasion diode I followed the characteristic of graph IV(a). However, the biasing current was not very steady and as a result the amplifier output reading was not very steady. Nevertheless a reading was obtained during one of the steadier moments. When the signal generator was substituted for the crystal, the generator read $F = 22$ in order to produce an equal amplifier output. By a similar calculation to that shown in Appendix I, a value of $f = 2.2$ was obtained for diode I using the measured values of $R = 130 \Omega$ and $C = 50 \text{ pF}$. This rather doubtful value of 50 pF for the capacitance of diode I has been used despite the fact that the actual value is probably lower than this, since this gives the largest value of $f$ and hence the poorest possible value of $r^2$. Thus,

$$r^2 = 0.705 \times \frac{2.2^2}{5} \times 2.2 = 0.68$$
Therefore in this case there is a smoothing factor at least as good as 0.68.

In previous work, the author (9) observed smoothing factors of less than unity in four insulator diodes constructed by soldering indium cathode contacts on to CdS crystals and using colloidal graphite for the anodes. From the measurements above, it is confirmed that values of $\gamma^2$ less than unity are also obtained for insulator diodes made with evaporated contacts of indium and gold.

The next diode to be tried as a noise source was diode J. An attempt to measure the capacitance of this diode, which was described in Chapter III, had proved unsuccessful because the noise of the diode prevented a bridge balance being obtained. The fact that diode J was noisy was confirmed when noise measurements were taken on it. When 5 mA current was passed through the diode, the amplifier output was very large and a noise generator output corresponding to $F = 25$ was required in order to produce an equal amplifier output. No value of $f$ was obtainable in this case, however, it can be said that a "smoothing factor" of $0.705 \times \frac{25}{5} \approx 3.5$ applies in this case, which means that diode J is giving considerably more noise than in the full shot noise case. As with diode I, the 5 mA biasing current was very unsteady in spite of the fact that the curve tracer plot had been perfectly steady. This is probably because an equilibrium of filled and unfilled traps is more readily obtained with an a-c. plot than at a fixed biasing voltage. Because the biasing current was so unsteady the amplifier output was unsteady and also very large because of the current fluctuations. The large noise in this case must be due to the spontaneous filling and emptying of traps.
In order to ensure that the large amplifier output in the above case was not due to amplifier instability as a result of differing input impedances, a mock diode was made up on a 9-pin valve base. This consisted of a 71 Ohm resistor with a 27k Ohm slider carbon resistor and a 50 pF beehive variable condenser in parallel mounted across pins 1,9. This mock diode was placed in the input to the amplifier and the output was observed as the resistance and capacitance were varied. No change in output was observed, which indicated that the amplifier was stable over a wide range of input impedances.

Despite the fact that for diode K the current was not taken up to 5 mA, which is the current chosen for the noise measurement comparison, a noise measurement was taken at 0.3 mA biasing current, which from graph VI(b) is seen to be a point within the approximate square law region. When used as a noise source, diode K gave an amplifier output of 1.5 µA. When the standard noise generator was substituted, a minimum amplifier output of 3 µA was obtained because of the minimum generator output of $F = 0.6$. This means that $R^2 < 0.705 \times 0.3 \times f$ where $f$ will be approximately unity in this case because of the large value of diode resistance. Thus $R^2 < 1.41$. However, if it is assumed that the law of the amplifier is approximately linear at these low outputs then an estimate for the smoothing factor can be made and this is then $R^2 \approx 0.7$.

No noise measurements were made on the diodes L,M,N because of their poor characteristics. The next diode to be tested for its noise properties was O. When biased at 5 mA current, this diode gave 12 µA amplifier output, which corresponded to a noise
factor $F = 2$. By a similar calculation to those shown in the Appendix I, a value for $f$ may be obtained using the measured values of a.c. resistance and capacitance for this diode namely, $R = 320 \, \Omega$, $C = 11 \, \mu F$. The factor $f$ has a value of 1.3 and so

$$R^2 = 0.705 \times \frac{2}{5} \times 1.3 = 0.37$$

At the same time, the diode $F$ was tested again and on this occasion

$$R^2 = 0.705 \times \frac{4}{5} \times 1.25 = 0.71.$$  This value is considerably larger than the first measured value of 0.18. However, when the characteristic was examined it was found that it no longer followed the graph II(a) but now followed the graph of II(b). As explained in Chapter III, the graph II(b) is consistent with the idea that a resistive barrier had appeared between the join of the crystal and the base and that this resistance was equivalent to $1.7 \, k\Omega$ by d.c. measurement. This barrier would contribute considerably to the noise, explaining the increased value of $R^2$ from this subsequent measurement.

After the characteristic of diode $P$ had been graphed, noise measurements were taken on it. At 5 mA biasing current, the diode gave an amplifier output which corresponded to a standard generator noise factor of 1.4. By a calculation similar to those in the Appendix I, a value for the factor $f$ is found using the measured values of a.c. resistance and capacitance namely $R = 330 \, \Omega$, $C = 7.7 \, \mu F$. This is $f = 1.27$ and so

$$R^2 = 0.705 \times \frac{1.4}{5} \times 1.27 = 0.25$$

The purpose of measuring all the values of $R^2$ at 5 mA biasing current is so that a comparison may be made between the various diodes.
### Table 4.1

<table>
<thead>
<tr>
<th>Diode</th>
<th>μ Thickness</th>
<th>Graph Slope</th>
<th>Bridge Resistance</th>
<th>Bridge Capacitance PR</th>
<th>Theoretical Capacitance PR</th>
<th>Factor f</th>
<th>Power of Law</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>F</td>
<td>16.3</td>
<td>340</td>
<td>340</td>
<td>5</td>
<td>3.15</td>
<td>1.25</td>
<td>0.18</td>
<td>0.71</td>
</tr>
<tr>
<td>I</td>
<td>10</td>
<td>-</td>
<td>130</td>
<td>( 525 )</td>
<td>2.2</td>
<td>2.58</td>
<td>0.68</td>
<td>-</td>
</tr>
<tr>
<td>O</td>
<td>13.3</td>
<td>340</td>
<td>320</td>
<td>11</td>
<td>( 3.0 )</td>
<td>1.3</td>
<td>2.64</td>
<td>1.67</td>
</tr>
<tr>
<td>P</td>
<td>6.6</td>
<td>330</td>
<td>330</td>
<td>7.7</td>
<td>( 3.9 )</td>
<td>1.27</td>
<td>2.04</td>
<td>0.25</td>
</tr>
<tr>
<td>Q</td>
<td>6.6</td>
<td>130</td>
<td>150</td>
<td>14.8</td>
<td>( 3.9 )</td>
<td>1.68</td>
<td>4.2</td>
<td>huge</td>
</tr>
<tr>
<td>R</td>
<td>10</td>
<td>580</td>
<td>300</td>
<td>4.7</td>
<td>( 2.6 )</td>
<td>1.27</td>
<td>1.6</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>6.6</td>
<td>120</td>
<td>150</td>
<td>( 7.0 )</td>
<td>( 4.0 )</td>
<td>1.64</td>
<td>2.15</td>
<td>-</td>
</tr>
</tbody>
</table>

* Change of characteristic.
However, this comparison will only be fair provided each value of $T^2$ is measured under the same conditions. Therefore, the values of $T^2$ compared should all be measured on the same occasion.

Noise measurements were made on diodes F, O, P in quick succession so that the conditions applying were the same in each case. For diode F, the noise factor was 5.4 giving $T^2 = 0.705 \times \frac{5.4}{5} \times 1.25 = 0.95$. For diode O, the noise factor was 1.3 and so $T^2 = 0.705 \times \frac{1.3}{5} \times 1.3 = 0.24$ and for diode P, the noise factor equalled 2 giving $T^2 = 0.705 \times \frac{2}{5} \times 1.27 = 0.36$. A table of the values of smoothing factor measured so far was made up. This table (4.1) shows the values measured on the same occasion in vertical columns.

The next diode to be tested for its noise performance was diode Q. When the output from this diode at 5 mA bias was applied to the amplifier, the reading on the amplifier output meter was off the scale at the top end. This apparently indicated that the noise was very large. However, diode P was tested at the same time and again the meter was off the scale. Since diode P, when measured previously, had given a smoothing factor of 0.36, it is unlikely that these large readings were due to noise. A more probable explanation is that the amplifier had not been allowed sufficient time to reach stability. A measurement of diode O at the same time gave a value of smoothing factor $T^2 = 0.40$ which is comparable with previous results for this diode and this indicates that either the amplifier had become more stable by the time this measurement was taken or else the input impedance of diode O produced better
amplifier stability than either P or Q. This latter explanation does not seem likely since diode P has much the same characteristics as Q. It, therefore appears that the amplifier had not been given sufficient time to reach stability.

It was now felt that a complete run through of the available diodes should be taken as there would be sufficient results for a comparison to be made. A run was taken on diodes F, I, O, P, Q in that order and the results are shown in column 6 of Table 4.1. (The evaluation of $r^2$ for diode Q involves the use of $f = 1.68$ and this has been worked out in Appendix I). A second run was taken immediately - this time in the order O, I, P, F, P, Q and these results appear in column 7 of Table 4.1. Comparison of columns 6 and 7 shows that the results are reasonably consistent, at least so far as orders of magnitude are concerned. Considering all the results so far obtained, the noise from diode F is fairly consistent after the low value observed initially. The increase in noise has been explained previously and is a result of the change of characteristic from that of graph II(a) to that of graph II(b). Diode I shows a considerable reduction in noise after the first measurement. A reduction in noise may also have occurred in the case of diode O, where later measurements are in general lower than the initially obtained result. The exception to this occurs in column 5 and this result may be high because of slight amplifier instability. Diode P exhibits an overall increase in noise with successive measurements. Diode Q is exceptional in that the values of $r^2$ obtained are greater than unity. This
large noise cannot be due solely to the diode shot noise and must be due in part to trap noise.

When the double diode R had been constructed, the 10µ section was tested for its noise properties using pins 1, 9. At 5 mA current the noise was equivalent to a noise generator output of \( F = 12 \) and using the value of \( f = 1.27 \), calculated by the method of Appendix I, this gives a value \( T^2 = 0.705 \times \frac{12}{5} \times 1.7 = 2.2 \). The leads were changed round and the 6.6µ section was tested using pins 1, 7. For this section the noise was equivalent to the noise generator output of \( f = 8.5 \) which means a value of \( T^2 = 0.705 \times \frac{8.5}{5} \times 1.64 = 2.0 \) where a value of \( f = 1.64 \) has been used. From this first measurement, it would appear that the thicker diode gives the more noise of the two, but since the values of \( T^2 \) are greater than unity more evidence would be required before this could be confirmed.

Again all the available diodes were tested for noise performance in a series of consecutive measurements. This method of measurement was repeated several times with intervals of days between each set. The results of these measurements are shown in columns 9 - 13 in Table 4.1. Considering the various results for diode 0, it is immediately obvious that overall the results are very consistent for this particular diode. Provided it is accepted that the larger value in column 5 is due to slight amplifier instability, as was argued previously, then only the first measured value of 0.37 is significantly higher than the others.

The various results of diode I are not so consistent. However, although there is an apparent lack of agreement between
The results, it may be significant that the considerable increase in noise occurs after each of the two characteristic changes. It is worth noting also that between the changes, the noise decreases with successive readings. A possible explanation for the last fact is as follows:

As explained previously, the characteristic changes that occurred for diode I were due to the application of a high voltage across the diode. It is thought that this high voltage produced local heating in the barrier, which encouraged donor diffusion, and so produced an n-type layer at the crystal surface. Since higher current flows after each change, these "breakdowns" must be thought of as successive reductions of a surface barrier. It is therefore a possibility that a small increase in the density of donors takes place each time the diode is used, since it is feasible that Joule heating will occur, raising the crystal temperature and causing diffusion. If this is so, then the surface barrier will be reduced a little each time the diode is used. This means that there will be a larger space charge of electrons at the virtual cathode and consequently there could then be a larger smoothing effect by the mechanism explained previously in Chapter II. Thus, this is a possible explanation for the reduction of noise with successive readings. However, this does not explain the great increase in noise that occurs after each breakdown. This cannot be explained satisfactorily.

The variations in the noise of diode F are due to deterioration of the current/voltage characteristic. As seen in Chapter III, the characteristic changed from that of graph II(a)
to that of graph II(b) and then to graph II(c). There were sudden increases in noise after each of these changes i.e., in column 2 and column 9. The greater noise in each case is of course due to the increase in "barrier" resistance. Between the changes of characteristic the noise readings are fairly consistent. The diode F broke after the measurement of column 10.

Diode P shows an increase in smoothing factor with each successive measurement until in column 9 there is a reduction to a value 0.18. The results obtained after this are consistently low, and in good agreement with each other. The results for diode Q show a similar effect but although there is an initial increase followed by a reduction in noise, the results obtained after the reduction are not very consistent. For the two sections of diode R, the results are rather confused. The 10μ section appears to show an increase followed by a decrease but the 6.6μ section displays a variety of results between 2.0 and 0.85 with no particular order about them.

Only diodes O, P show any degree of consistency and this only in the later readings. It is probably significant that the two diodes giving the most consistent results are in fact the diodes with the least noise. This is reasonable because in these cases the variable contributions to noise, e.g., trap noise, must be at a minimum. For both these diodes, the earlier results show higher values of $\pi^2$. For diode O only the first result is significantly higher than the others. In the case of diode P, the earlier results show a tendency to increase until there is a sudden decrease in the noise and consistent values of $\pi^2$ are obtained. Both diode Q and the 10μ section of diode R show a
similar sort of tendency where the values of smoothing factor increase to a maximum and then decrease. Since the maximum values in each case do not appear in the same column, there can be no question of this being an amplifier effect.

Up till now it has been assumed that the noise is due to the spontaneous fluctuation of the s.c.l. current through the insulator diode and that this is equivalent to a pure current generator $i^2 = 2eI R^2 \Delta f$ with the diode a.c. impedance in parallel with it. However, the possibility that the noise is due to the random motion of thermally excited electrons acting across the resistive elements of the diodes must be considered. This model is equivalent to a pure current generator $\bar{I}^2 = \frac{4kT \Delta f}{R}$ where $R$ is the diode a.c. resistance, with the diode a.c. impedance again in parallel with it. The first model, which considers the noise to be shot noise, has been assumed, the correct one so that this is equivalent to the observed noise. This can be compared to the noise obtainable by the resistive model. A ratio can be obtained

$$\frac{\text{observed noise}}{\text{possible resistive noise}} = \frac{2eI R^2 \Delta f}{\frac{4kT \Delta f}{R}} = \frac{e}{2kT} \cdot R I R^2 = 20RI R^2$$

and this ratio can be evaluated since all these quantities are known for a particular diode. Consider the diodes described in Table 4.1. Taking the values of $R^2$ as in column 13 and $I = 5$ mA in all cases, the values of the above ratio can be found. Table 4.2. shows the results.

Note that $T$ is the absolute temperature of the electron cloud, which may be different from that of the crystal.
Table 4.2

In several cases, the value of $\gamma^2$ chosen is the smallest observed, but even using the smallest observed values throughout, there are no instances where the observed noise is not at least twice as great as could be produced by the resistance theory.

Even considering the largest possible experimental errors, there is still an overwhelming weight of evidence to show that the observed noise could not be due to thermal fluctuations in current.

Although the ratios are large enough to be sure that resistive noise could not be the sole contributor, it is however, still a possibility that it could produce a significant contribution to the noise. If the ratios had been very large, then this would have shown that the possible resistive noise was
very much smaller than the observed noise and therefore would have produced a negligible contribution. This is not so and, as a result, there is an alternative method of regarding the noise results obtained. This is to consider the noise as being due to both shot noise and resistive noise rather than shot noise only. The a.c. circuit of the diode consists of the diode resistance with its capacitance and an external 71\,\Omega in parallel with it. Now each type of noise can be depicted as a pure current generator with the diode resistance R in parallel with it. Thus, if the diode resistance gives rise to both shot noise and resistance noise then the two current generators will be in parallel. The mean square noise current is obtained by summing the mean square contributions. Thus

$$\text{Total } i^2 = (2eI^2 f^2 \Delta f) + \left(\frac{4kT \Delta f}{R}\right)$$

and this has been made equal by experimental observation to

$$2eI^2 f^2$$

where the $f^2$ are the smoothing factors worked out in Table 4.1.

Therefore,

$$\left(2eI^2 f^2 \Delta f\right) + \left(\frac{4kT \Delta f}{R}\right) = 2eI^2 f^2 \Delta f$$

and so

$$\left(\frac{2eI^2 f^2 R}{4kT}\right) + 1 = \frac{2eI^2 f^2 R}{4kT}$$

Thus

$$(20RI^2 f^2) = (20RI^2 f^2) - 1$$

from which values of the new smoothing factor $f^2$ can be obtained. These are shown in the last column of Table 4.2, and are calculated using the $f^2$ values of the fourth column of that table.
It is impossible to say which interpretation of the results is the correct one. However, despite this, the basic fact that the observed noise is less than the full shot noise is not affected. Furthermore, although the new values of smoothing factor $\gamma_2^2$ are naturally less than the original values, the relative magnitudes of the values in each set are not very different. Any qualitative comparison of the smoothing factors in a set is not much affected by whether it is the set of original values or the new set. For example the 10μ section of diode R shows the largest value of smoothing factor, whether the original $\gamma_2^2$ values are considered or the new $\gamma_2^2$ values. Therefore, as far as qualitative comparisons of smoothing factors are concerned, only the values in table 4.1. will be considered and it will be assumed that any relation holding for these values would also hold for the $\gamma_2^2$ values.

One of the most interesting comparisons that can be made is between values of $\gamma_2^2$ and the crystal thickness. In a vacuum diode, the individual charges "$e$" can be thought to move right from the cathode to the anode and consequently the charge induced on the anode by the electron moving right across the diode thickness $d$ is given by $Q = \int_0^d \frac{e}{d} \, dx = \frac{e}{d}$, which is a well known result. However, in a solid state device e.g. insulator diode, charges can be trapped and deflected with the result that each charge "$e$" only moves a distance $\mathcal{L}$ on average and not the full distance $d$. As a result, the charge induced on the anode is $Q = \int_0^\mathcal{L} \frac{e}{d} \, dx = \frac{e\mathcal{L}}{d}$ and so, for noise considerations the "shots" of charge should be thought to be of value $\frac{e\mathcal{L}}{d}$ and not $e$. The shot noise would then be given by
\[ i^2 = 2 \frac{e \ell}{d} I \Delta f \]

By this way of thinking, a value of smoothing factor \( r^2 = \frac{\ell}{d} \) would be obtained. If, in the first instance, it is assumed that the average distance \( \ell \) travelled by an electron in an insulator diode is the same for all diodes then this theory predicts that the smoothing factors are inversely proportional to the thicknesses of the various diodes. Consideration of table 4.1 quickly shows that this idea is certainly not true. Comparing, for example, the two diodes with the lowest and most consistent results i.e. diodes 0, P then the thicker diode has the larger value of \( r^2 \). Likewise, comparing the two sections of diode R, although the results are far from consistent, nowhere does the 10\( \mu \) section show a smaller value of \( r^2 \) than the 6.6\( \mu \) section. There is no question of the values of smoothing factor being proportional to thickness either since diode I (10\( \mu \)) shows a larger value of \( r^2 \) than diode 0 (13.3\( \mu \)). However, it was assumed that \( \ell \) was a constant for the various diodes. This is probably not true since the average distance travelled by an electron before capture or deflection will depend to some extent on the number of traps present and possibly on their distribution. So it is possible that \( r^2 = \ell/d \) despite the fact that \( r^2 \) is not inversely proportional to \( d \). If this theory holds then \( r^2 \times d = \ell \) and a value of \( \ell \) can be obtained for each diode. These values of \( \ell \) should bear some relation to the traps present in each diode. However, there is not much information on which to estimate trap content. The traps-filled voltage limit, which might appear as a threshold voltage, would give an estimate of deep traps and the power \( n \) of the law \( I \propto V^n \) bears some relation to the traps distribution. However, neither of these quantities shows any relationship to the values of \( \ell \), which is
not surprising when the following point is considered. For diodes of
the same thickness, a small value of \( \dot{\ell} \) means a small value of \( \gamma^2 \)
from the definition, \( \gamma^2 = \frac{\ell}{d} \). However, a small value of \( \ell \)
by physical reasoning must be due to the presence of a large number
of traps and this means a large value of \( \gamma^2 \) because of trap noise.
Thus, any smoothing effect due to a small value of \( \ell \) would be
masked by the fact that there would be a large trap noise in such a
case. Thus, it is impossible to show whether this theory holds in
practice or not.

Having shown that there is no direct relationship between the
values of \( \gamma^2 \) and the diode thickness, a relationship between \( \gamma^2 \)
and the other parameters must be searched for. Examination of table
4.1. shows that no obvious law holds connecting \( \gamma^2 \) and a.e.
impedance or the capacitance or the power n of the law \( I \propto V^n \).
However, there is one fact that is of interest and this can be seen
by examining the log plots for the various diodes. The log plots for
both diodes O and P differ from the others by the shape of the
curvature. Before the linear portion, the curvature is concave away
from the log V axis. For all the others it is either convex or else
linear over the whole range. The shape of the curved portions
indicated that for diodes O,P an exponential region might apply,
that is for certain current ranges the current might follow a law
\( I = A e^{dV} \), where \( A = \) a constant. Taking logs of both sides of this
equation gives

\[
\log_{10} I = \log_{10} V + dV \log_{10} e + \log_{10} A
\]

or

\[
\log_{10} I = \log_{10} V = d (\log_{10} e) \cdot V + \log_{10} A
\]
Graph XIV (c) ((Note C)

\[ \text{Slope} = -0.329 \]

\[ R = \text{Log } V \]

\[ d = 0.35 \]
Graph XIV. (b) (diode P)

Slope = 0.216

\[ \log I = \log V \]
Thus by plotting \((\log I - \log V)\) against \(V\), a check can be made whether diodes 0, P follow such a law. This plot is shown for diode 0 in graph XIV(a) and it can be seen that the plot is linear until after 2 volts. This corresponds with the change over point of graph X(b) and shows that the exponential region merges into a power law region around 2\(V\). Similarly, graph XIV(b) shows that diode P follows an exponential law before 2 volts and a power law after this voltage. Amongst the diodes tested for noise, only diodes 0, P exhibited exponential regions and these two diodes are the least noisy. It was shown by Rose (2) that an exponential law of the type \(I \propto V e^V\) applies when there is a uniform distribution of trap energies below the conduction band. However, no particular connection can be seen between the uniformity of trap energy distribution and the small noise so it may be no more than a coincidence that diodes 0, P are the only two to exhibit exponential regions.
Conclusion

The first conclusion obtainable from the above noise considerations is that the noise observed is less than the full shot noise. On the assumption that the noise is due to random fluctuations of the diode current, this means that values of smoothing factor less than unity are obtained. The author, in previous work, observed smoothing factors of less than unity in some insulator diodes constructed by soldering indium cathode contacts on to CdS crystals and using colloidal graphite for the anodes. The above results confirm that values of $r^2$ less than unity are still obtained for insulator diodes made with evaporated contacts of indium and gold.

From the observations of values of $r^2$ over a period of time, the most significant result is that the two diodes with the most consistent results over a number of measurements are the diodes also showing the least noise. This shows that the variable contributor to the noise, namely trap noise is at a minimum for these diodes. For the other diodes, in general, there is a tendency for the noise to become smaller with successive measurements. A tentative explanation for this is that with use more diffusion of donor centres takes place which results in a larger space-charge of electrons collecting at the virtual cathode. This in turn results in a greater smoothing and hence less noise. This process is interrupted by changes of characteristics.

It has been shown that the noise produced by the insulator diodes could not be due to the random motion of thermally excited electrons acting across the diode a.c. resistance, but the results are such that this could be a significant contributor to the noise.
When this is assumed, new values of smoothing factor are obtained and these are much smaller than those initially obtained. However, so far as relative size is concerned, these smaller results bear much the same relationship to each other as do the initial ones. Thus, although it is impossible to say which interpretation is the correct one, a comparison of the values of $\gamma^2$ in a particular set is possible and the results would hold for the other set.

So far as comparing the values of $\gamma^2$ with the various crystal parameters is concerned, very little can be said in conclusion. It was quickly demonstrated that smoothing factors bear no particular relation to crystal thickness and that if a relationship of the type $\gamma^2 = \frac{2}{\alpha}$ did hold, then any smoothing effect due to a small value of $\alpha$ would be masked by trap noise. Similarly, the smoothing factors appear to bear no relation to any of the other crystal parameters. However, if there was such a relationship, then it could probably be masked by other contributions to the noise. Only one observation of possible significance was made. This was that the two diodes having the least noise were exceptional in that they both showed exponential sections in their characteristics. However, although the presence of an exponential region indicates a uniform distribution of trap energies, there seems to be no particular connection between this uniformity of trap energy distribution and the low noise exhibited by these two diodes.

These results show that much more detailed knowledge would be required of the exact workings of these insulator diodes, before a theory predicting values of smoothing factor could be proposed. In particular, it is felt that a more detailed knowledge of trap densities and distribution would be useful in order to separate the various contributions to noise in insulator diodes.
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\( Y_3 = \frac{1}{71} \quad \therefore Y_3 = 1 \quad \text{and} \quad \gamma_3 = 1 \)

\( Y_1 = \frac{1}{180} + j \ 2\pi \times 20 \times 10^6 \times 18 \times 10^{-12} \)

\[ Y_1 = 0.0056 + j0.00226 \]

\[ \therefore y_1 = 0.389 + j0.158 \]

\[ \because y_1 + y_3 = 1.389 + j0.158 \]

\[ \therefore \text{power} = \frac{\gamma_1^{\text{in}}}{\gamma_1} = \frac{0.389}{1} = 0.198 \]

\[ \therefore y_1^{\text{in}} = 0.48 + j0.46 \quad \text{(by Smith Chart)} \]

\[ \therefore y_3 + y_1^{\text{in}} = 1.48 + j0.46 \]

\[ \therefore \text{and equivalent impedance} = 0.63 - j0.18 \quad \text{(by Smith Chart)} \]

\[ \therefore \text{power} = \frac{i_\text{gen}^2}{R_3} = \frac{i_\text{gen}^2}{0.63 \times 70} \]

\[ \therefore \text{power} = i_\text{gen}^2 \times 44.2 \]
For diode $F$, $R = 340 \, \Omega$ and $C = 5 \, \text{pF}$

\[ y_4 = \frac{1}{71} + \frac{1}{340} + j\omega \cdot 5 \times 10^{-12} \]

\[ y_4 = 1 + 0.206 + j0.044 \]

\[ y_4^* = 1.2 - j0.06 \quad \text{(by Smith Chart)} \]

\[ y_2 + y_4^* = 1.589 + j0.098 \quad \text{(since } y_2 = y_1 \text{)} \]

and conductance $G_2 = \frac{1.589}{70} = 0.0227 \, \text{\Omega}^{-1}$

\[ \therefore \text{Power} = v_2^2 \frac{G_2}{2} = v_2^2 \times 0.0227 \]

\[ y_2^* = 0.45 + j0.35 \quad \text{(by Smith Chart)} \]

\[ y_4 + y_2^* = 1.636 + j0.394 \]

and equivalent impedance $= 0.58 - j0.14$

\[ \therefore \text{Power} = \frac{i_2^2}{\text{crystal}} R_4 = \frac{i_2^2}{\text{crystal}} \times 0.58 \times 70 \]

\[ \therefore \text{Power} = i_2^2 \times 40.5 \]

\[ f = \frac{R_2}{R_4} \cdot \frac{G_2}{G_1} = \frac{44.2}{40.5} \times \frac{0.0227}{0.0198} \quad \therefore f = 1.25 \]
For diode Q, \( R = 150 \ \Omega, \ C = 14.8 \ \text{pF} \)

\[
Y_4 = \frac{1}{\jmath 71} + \frac{1}{150} + \jmath \omega \times 14.8 \times 10^{-12}
\]

\[
y_4 = 1 + 0.466 + j0.13
\]

\[
y_4^\infty = 1.45 - j0.12 \quad \text{(by Smith Chart)}
\]

\[
y_2 + y_4^\infty = 1.839 + j0.038
\]

and conductance \( G_2 = \frac{1.839}{70} = 0.0263 \ \Omega^{-1} \)

\[
\text{Power} = v_2^2 G_2 = v_2^2 \times 0.0263
\]

\[
y_4 + y_2^\infty = 1.896 + j0.48
\]

and equivalent impedance = \( 0.5 - j0.12 \)

\[
\text{Power} = \frac{i^2}{\text{crystal}} R_4 = \frac{i^2}{\text{crystal}} \times 0.5 \times 70
\]

\[
\text{Power} = \frac{i^2}{\text{crystal}} \times 35
\]

\[
f = \frac{R_3 G_2}{R_4 G_1} = \frac{44.2}{35} \times \frac{0.0263}{0.0198} \quad \therefore f = 1.68
REFERENCES