IRRADIATED SILICON DETECTORS:
a relaxation semiconductor analysis

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ABSTRACT

There is now overwhelming evidence that irradiated silicon, and irradiated and non-irradiated semi-insulating GaAs material is a relaxation semiconductor and this needs to be allowed for in measurement and analysis. This approach explains such observations as: Ohmic I-V, negative capacitance, capacitance peak with voltage, constant field regions and the detailed shape of the C-V curve at medium voltages and just below full depletion. As well as indicating the appropriate method to calculate such quantities as the effective space charge there are implications in the design and optimisation of such devices.

The work in this form will only be presented as a ROSE Technical Note. A more detailed description with full justifications for the conclusions presented here is being prepared for device journals.

For ease of reading the supplementary explanation has been placed in boxes. The references supply even more detail.

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INTRODUCTION

After irradiation silicon diodes do not behave like the usual diodes. You only have to look at the I-V curve to see this. The problem is that most of the properties, eg C-V, give data which looks rather like what is normally expected so it is possible keep on using the normal analysis without any real worries provided that you are not too concerned about the deviations from ideal behaviour. In fact very severe changes have taken place to the physics of the material and the approximations which are assumed (without realising it usually) in the equations used in the analysis no longer work. The material has changed from a *'lifetime'* semiconductor to a *'relaxation'* semiconductor. Here we will describe in a qualitative and semi-quantitative way what is happening in the devices, how to analyse the data and what this implies in the design of 'better' devices. Most of this description which is directed to irradiated silicon detectors also applies to all high resistivity or semi-insulating (SI) devices such as SI GaAs diodes and detectors but in those cases there are many defects of various types and properties so that the overall properties of the devices are obscured.

What follows is a recent interpretation of very well established, but unfamiliar theory. The conventional expositions of relaxation semiconductor theory have not been well related to experimental results or experimental variables. This has been, in part, because there has not been a good ('clean') experimental system to study. Irradiated silicon supplies this system.

The semiconductor industry has paid most attention to the pure semiconductor material with considerable extrinsic doping and has mainly used silicon because of the valuable properties of devices made from such 'lifetime' materials. However by 1972 considerable work had been carried out on another class of semiconductor, 'relaxation' material typified by the work of van Roosbroeck and Casey[1] and Manifacier[2] and the seminal review of Queisser[3]. A more recent review is by Haegel[4]. Since then, studies of 'relaxation' semiconductors have been few, they are not mentioned in many text books and most present practitioners are not familiar with the concepts even though these materials now occur in common electronic devices. Recent work with relaxation semiconductors has been involved with more detailed consideration of the theory or very detailed modelling of specific special cases. However the appropriate limits and experimental quantities are not usually known and the calculations have not been related to experimental observations. There is a particular problem in recent modelling that the density of generation-recombination centres appears to be considerably underestimated.

Relaxation material can easily create, or recombine, electron-hole pairs. This is normally a slow process since it requires thermal generation across the energy band gap. However two-step thermal excitation through defect states at the mid gap energy (generation-recombination (g-r) centres) is many orders of magnitude more efficient than thermal excitation by the direct, one-step process. The irradiation creates many such defect states near mid gap, as well as other traps.

The conventional 'lifetime' material has $\tau_D \ll \tau_0$. A 'relaxation' material has $\tau_D \gg \tau_0$. Here $\tau_D = \rho\varepsilon\varepsilon_O$ (ρ is the resistivity) is the dielectric relaxation time which is the

time in which a space charge is neutralised by the flow of the free carriers drawn in by the charge but slowed down by the resistance. It is the bulk equivalent of an RC time constant. The minority carrier recombination lifetime, τ_0 , is the time constant for recombination of non-equilibrium electron-hole pairs or excess minority carriers. It is also the time to generate electron-hole pairs to reach equilibrium. In lifetime material charge flows in rapidly to cancel any non-equilibrium space charge and local charge neutrality is a basic equilibrium requirement. In relaxation material there is a local generation or recombination of carriers. A material will become relaxation-like if it has high resistivity (near intrinsic or compensated) and a large density of defect generation-recombination (g-r) electronic levels near the middle of the energy gap which can readily interact alternately with electrons and holes. Such traps can be produced by radiation damage (as in irradiated silicon devices) or some dopant impurities (as in semi-insulating GaAs or Au doped Si).

Relaxation material has properties which appear very strange to those who are familiar with lifetime material. If carriers are injected the resistivity normally *increases*. Excess charge travels with the *majority* carrier mobility and sign etc.. As well as unexpected bulk properties the presence of contacts causes even more complexity.

For simplicity here we only consider the case of a single Schottky-P^{--} or N^{+}-P^{--} junction. If a reverse bias is applied to an N^{+}-P junction made of relaxation material the free carriers are not completely removed to cause a depletion region since new e-h pairs are created *'on demand'* to fill the space.

This results in this region having a single quasi-Fermi level near mid-gap where the g-r process is most efficient. The Fermi level is pulled to near the midgap, intrinsic level.

Here, for a steady state in the charge distribution the current flows are continuous; $n_0\mu_n = p_0\mu_p$:and with $n_0p_0 = n_i^2$ we get $n_0 = p_0(\mu_p/\mu_n) = n_i(\mu_p/\mu_n)^{1/2}$ and in this steady state, n_0 and p_0 are independent of the specific material, contacts or traps. Also the resistivity is the *'maximum resistivity'* given by $\rho^{-1}_{max} = (2\ e\ n_i\ (\mu_n\mu_p)^{1/2}) \sim (8 \times 10^8\ \Omega\ cm)^{-1}$ at room temperature for GaAs and $(3 \times 10^5\ \Omega\ cm)^{-1}$ for silicon. This is a dynamic property also independent of the details of the material.

The features which are characteristic of diode devices made from relaxation material and which cannot be explained by lifetime theory are [3,5,6]:

- ohmic I-V characteristics at the maximum resistivity. Fig 1 shows the I-V characteristics for a lifetime diode (the lowest current curve). For diodes after irradiation at higher levels to make the material more relaxation-like and the curves move closer to the Ohmic line at the maximum resistivity. [7]
- a low-voltage capacitance peak in reverse bias and a negative capacitance in forward bias. Fig 2 shows these as the irradiation is increased (Φ1-4).[8]
- 'built-in charge' effects (these have largely been deduced from the detection efficiency of particle detectors)[9]
- shot noise reduction in the 'Ohmic' device

ANALYSIS

Current-Voltage

The general and exact analysis is very involved and needs a full numerical analysis involving all the trap and g-r centre densities, cross-sections and energies, but many of the parameters are not known. Here we follow a semi-quantitative analysis which gives physical insight and allows some calculations to be made. We use a very schematic diagram of the charge distribution and bands. The properties of the system is very non-uniform along the direction of current flow as the Fermi level occurs in different positions relative to the band edges. We consider first the case of a semi-infinite diode with an Ohmic contact at the end of the semiconductor far from the junction.

The first case is the case with zero space charge so that the whole diode is a region of Ohmic relaxation material with Ohmic characteristics. The resistance is

$$1/G_0 = R_0 = \rho_{max} d/A$$

where d is the width between the contacts and A is the diode area. The blocking properties of the junction have disappeared. Although it is an Ohmic resistance its physics is not the same as a normal resistor. Although this resistance is a good quantity which depends little on the details of the diode we do not usually know ρ_{max} because the mobilities cannot easily be measured and the material is full of scattering defects. The values for the pure material are used as the default. In this approximation this result is true for forward bias also since, as with lifetime diodes, the built-in voltage depletes the whole device.

Now we consider the case with very small space charge. This corresponds to a low donor/acceptor density and a low deep level density. Such a low density is the desirable case for detectors so that the sensitive region is wide.

Reverse bias

This is the polarity for reverse voltage for a lifetime diode or the polarity which has lower conductance at high voltages.

A very schematic band diagram is shown in Fig. 3. The total voltage drop across the 'depleted' part of the diode consists of three parts:

1. that due to the current through the Ohmic region which is the relaxation-like section of width $W_1(V)$ and maximum resistivity ρ_{max} to give a resistance $R_o(V) = 1/G_0 = \rho_{max} W_1(V)/A$, where A is the diode area. Since W_1 is not well defined we will replace the full expression for $R_o(V)$ by the value derived above, R_o, equal to that of a diode of maximum resistivity and full depletion ($W_1 = d$). This works quite well since the approximation that the width is the full voltage-independent geometric width and the approximation that the mobility is that of the undamaged material work in opposite directions.
2. those due to charge dipole layers:
   i) the normal *built-in voltage,* V_{bi} , which is which is here equal to half the bandgap (about 0.5V for silicon and hence often negligible) which is the band

discontinuity. We represent this by a region of free carrier space charge n_f over a distance W_o or a built in charge of $Q_o = n_f W_o$. There is a corresponding charge within the contact. There are insufficient ionised defects to account for the built-in voltage and the fact that the material is relaxation-like forces a rapid chage in the position of the Fermi level at the contact.

ii) the space charge in the depletion width (and the corresponding charge in the contact). The length $W(V) > W_1(V)$ is the total 'depletion width' where the traps of density n_t. are empty. This includes the regions which are relaxation-like and also where there are separate quasi-Fermi levels. This can be a complex region since the traps may be of different depths (see later) and there are also donor/acceptors which are always ionised.

Thus

$$V = R_o I + eW^2 n_t/2\varepsilon\varepsilon_o + Q_o W_o/2\varepsilon\varepsilon_o \quad (1)$$

or

$$V - V_{bi} = R_o I + eW^2 n_t/2\varepsilon\varepsilon_o \quad (2)$$

since $V = eW^2 n_t/2\varepsilon\varepsilon_o$ across the depletion region

and $V_{bi} = eW_o^2 n_f/2\varepsilon\varepsilon_o = Q_o W_o/2\varepsilon\varepsilon_o$

In a normal diode with g-r centres the quasi-Fermi levels are different for the electrons and holes and there is a generation current proportional to the depletion width and hence varies as $V^{1/2}$. Here we assume that the relaxation width is fairly voltage independent and the generation current is generated over the whole depletion width.

Thus $I = n_{gr} WA$

where n_{gr} is the effective density of g-r centres and includes a factor to account for their efficiency, and

$$V - V_{bi} = R_o I + en_t I^2/2\varepsilon\varepsilon_o n_{gr}^2 A^2 \quad (3)$$

or

$$V - V_{bi} = R_o I + R_1 I^2 \quad (4)$$

Here V_{bi} is half the band gap and hence is usually negligibly small. The first term on the RHS corresponds to the Ohmic relaxation contribution and the second to that of the space charge dipole.

If we take the case where the irradiation fluence Φ produces both traps and g-r centres so that

$$n_t = \beta\Phi$$
$$n_{gr} = \alpha\Phi$$

then

$$V - V_{bi} = R_o I + e\beta\Phi I^2/2\varepsilon\varepsilon_o(\alpha\Phi A)^2 \quad (5)$$

The change from Ohmic to $V^{1/2}$ occurs when these two terms are equal at $V_t = V_{bi} + 2R_o I_t$ and $I_t = 2(\varepsilon\varepsilon_o/e)R_o A^2(\alpha^2/\beta)\Phi = R_o/R_1$.

There are several approximations made here but the fit seems to be reasonable and we know little about the quality of the appproximations.

This explains the basic shape of the I-V curve, shown in Fig. 4, its temperature dependence and the observed constant field (Ohmic) region [10].

Forward bias

Experimentally we find that in forward bias the I-V fits

$$I = G_o V \exp V/V_o \qquad (6a)$$

or more probably

$$I = G_o V \exp Vd/E_o \qquad (6b)$$

Here $V_0 = E_0/d$ is a fitting parameter and the particular form prefered depends on the physics involved. This is the fitting function which was used for other relaxation materials years ago. The values of V_o and E_o should be recorded as a simple measure of the degree of relaxation-like-ness.

We concentrate on the free carrier concentration next to the junction which provides the fixed potential step

$$V_{bi} = E_g/2 = eW_o^2 n_f/2\varepsilon\varepsilon_o = Q_o W_o/2\varepsilon\varepsilon_o = F_{pk} W_o/2 \qquad (7)$$

As the material gets more relaxation-like the transition region, W_o, becomes shorter and the peak field, F_{pk}, gets bigger. In forward bias the energy diagram becomes a step down due to this space charge and then a linear ramp up due to the voltage drop along the relaxation-like region. There is increased injection at the contact as the peak of the step is reduced by the field. This is a field-assisted barrier lowering. The quantity V_0 or E_0 is a good measure of the relaxation-like-ness of the material.

Thus the I-V characteristics can be a valuable record of the condition of the device and the forward and reverse characteristics should be recorded as standard procedure.

Capacitance

The ac depletion capacitance is a measure of the incremental space charge. In the samples considered there are several effects occuring simultaneously which can be confused. These are the effect of the relaxation region, the behaviour of the deep traps and the effects of the built-in charge at each contact.

(i) The effect of the relaxation region: reduced voltage

Following the above analysis we can see how to use the C-V data to obtain useful information. If you look at the C-V data it has a peak at low voltages and decreases faster than $V^{1/2}$ at high voltages so that the normal analysis to determine the space charge from the slope of the curve is not possible. The analysis which should be used in the analysis is to decrease the applied voltage by both the built-in voltage (V_{bi} ~ 1/2 E_G/e) and the voltage drop across the relaxation section (R_oI).

Thus V becomes

$$V - V_{bi} - R_o I = eW^2 n_t/2\varepsilon\varepsilon_o \qquad (8)$$

and since $C = A\,\varepsilon\varepsilon_o/W = A(en_t\varepsilon\varepsilon_o/2(V - V_{bi} - R_oI))^{1/2}$ (9)

we can plot $1/C^2$ against the reduced voltage

$$1/C^2 = (2/A^2en_t\varepsilon\varepsilon_o)(V - V_{bi} - R_oI) \quad (10)$$

and the slope gives n_t the density of the space charge, or ionised traps.

This needs a knowledge of the I-V data. However it has been found that, to the approximations involved, we can use alternatively either $(V - V_{pk})$ or $(V - V_{BI})$ where V_{pk} is the voltage of the peak in the curve and V_{BI} is the fitted voltage in order to obtain a $V^{1/2}$ fit. This is shown in Fig. 5 for silicon diodes at increasing fluence.

This gives n_t . The average value at full depletion n_{eff} is also calculated this way using the voltage at full depletion V_{dep} but since the correction voltages are small there is little effect on the final value.

(ii) The effect of deep traps: frequency effects

The next effect is that the C-V curves are very frequency dependent and the capacitance decreases at high frequency. This is an effect which is not related directly to relaxation effects but to the presence of deep traps in the semiconductor due to the irradiation, or perhaps doping. These are not situated near mid-gap and are sufficiently different in behaviour from the g-r centres to be considered as a separate category.

A schematic band diagram is shown in Fig. 6. Where the Fermi level crosses a trap level an AC voltage will cause periodic changes in the occupancy of the trap. It empties by thermal activation which is slow for deep levels at room temperature. The filling is not fast either since the density of free carriers is low. If the AC frequency is lower or higher than the trap/detrap frequency then the space charge due to this trap is seen or not seen. The system is very complex with layers of different densities of space charge. Note that the donors/acceptors are shallow and free and always respond. It is normal in analyses to assume that their density is higher than the deep level density but this may not be true here.

To obtain results which are well defined the data should be taken for the high temperature/low frequency limit which is as close to the DC behaviour as possible.

(iii) The effect of the built-in charge: negative capacitance and the capacitance peak

Samples show a negative capacitance in forward bias. This means that there is a decrease in charge for an increase in voltage. It is not called an inductance since the sample has the geometry of a capacitor and behaves as such at other biasses. This negative capacitance also reduces the positive capacitance at low reverse bias to produce a peak at a few volts. These are pure relaxation effects and are caused by the presence of a built-in charge of free carriers at the boundary of relaxation material and a contact. This charge dipole region also has a large field which separates the charge even at low bias and will be particle sensitive.

Consider the band diagram in Fig. 3. Within the low resistance contact the Fermi level is near the conduction band edge and in the relaxation semiconductor the Fermi level (or strictly the two identical quasi-Fermi levels) is near mid-gap since the material is compensated, the density of g-r centers is very high and the g-r processes are very rapid. Far from the junction the material becomes P-type. The potential step, V_{bi}, in the energy bands of about half the band gap at the junction has to be established by a charge dipole

consisting of a high concentration of positive charges in the highly doped contact and free electrons in the semiconductor where there are insufficient fixed ionised traps to create an adequate space charge. The more relaxation-like the material becomes the larger the free charge density and the narrower this free charge layer is, Eq.7. In reverse bias these free carriers have the same sign as the fixed space charge. It can be seen that the presence of a large space charge density in the depletion region will reduce the effect of the free carriers. In this example the conventional depletion region extends to W, the free carrier built-in charge due to relaxation effects extends to W_0 and the bands are near mid-gap so that the generation-recombination process is efficient and the material is relaxation-like to a distance of W_1. At distances greater than W the material is P^- and not relaxation-like since the Fermi energy is far from mid gap so that the g-r process through the centres is not efficient.

The AC depletion capacitance in reverse bias is produced in a lifetime material (or relaxation material if the space charge due to traps is low) by an increment of voltage removing free carriers from the far edge of the depletion region (W) to reveal the fixed space charge of the traps and increase the charge dipole which balances the extra applied potential. In forward bias the same process also happens at a slightly smaller value of W but for a relaxation material there is also injection of holes which recombine easily with the electron free carriers of the dipole near the junction and hence decrease the charge dipole. Although the built-in voltage is constant at $V_{bi} = eW_o^2 n_f/2\varepsilon\varepsilon_o = Q_o W_o/2\varepsilon\varepsilon_o$ there can be a change in the charge. This produces a large negative capacitative effect because the recombination process is strong and the charges involved are so close (at W_0) to the contact charges. The resultant capacitative effect of these two processes of the opposite sign is determined by how relaxation-like the material is, that is the density of g-r centers, and the trap ionised space-charge density.

(iv) The effect of the built-in charge at the far contact: far end effects

Other effects of the built-in charge are those which are due to that which exists at the far end of the diode where there is a contact to the near-intrinsic material. The band bending is the same as that at the end which we have been considering. This local charge dipole will produce a small region of high field, which is large enough to enable charge separation and hence be a sensitive region for particle detection, as observed[9]. Also there is a rapid drop in the capacitance as the voltage reaches near full depletion. Here the space charge reaches the contact but the density of free carriers, of the opposite sign to that of the space charge, is high. The capacitance is the charge change for a voltage change and hence decreases rapidly. To reduce these effects one can use an Ohmic contact at the far end or perhaps grade the doping to make the material with a larger space charge near that contact.

<u>The relaxation analysis explains the following experimental observations</u>

I-V: Ohmic and $V^{1/2}$ shape in reverse bias, Ohmic and exponential in forward bias, Ohmic magnitude.

Constant field regions, large field regions near contacts.

C-V: frequency dependence due to traps, negative capacitance and capacitance peak, analysis method for 'trap density', capacitance dexcrease near full depletion.

Since the analysis methods must be changed as the material becomes relaxation-like we can assume a constant damage rate α and β through type inversion to a good approximation.

IMPLICATIONS FOR DETECTOR DESIGN

This analysis using relaxation semiconductor theory gives insight which can suggest ways that the detector design may be improved, or designed for a specific application.

A All analysis should assume relaxation-like material.

B The device will be near-Ohmic and the current drain of the detector can be predicted accurately from ρ_{max}.

C Although the device has an Ohmic resistance its physics is not that of a conventional resistor. It is not in equilibrium in so far as a current flow is necessary. It thus shows shot noise rather than thermal noise at voltages greater than kT/e. However, the full shot noise equation assumes that the charge carriers are crossing the device independently to give the current noise spectral density $S_i = 2eI$. In the relaxation diode case the electron-hole pair charge carriers are generated 'on demand' and this will be where the is a local current deficiency. The generation rate is now no longer uncorrelated so a reduction in the theoretical value given above is expected. This has been observed[11].

D Because the physics, and hence the methods of analysis of detectors changes with increasing irradiation as more g-r centres are produced there seems to be a reasonable assumption that the introduction rates of g-r centres (α) and of *net* acceptors (β) are probably constant through type inversion rather than following some rather complex function as has been assumed.

E With lifetime material analysis an acceptable depletion voltage can be best obtained if the material is initially as N-type as permissible so that the irradiation makes it more P-type and it ends up type-inverted to the maximum permissible amount at the end of its life. This analysis needs modification to allow for relaxation effects.

F Better stability would be obtained by starting with an N+ P- Ohmic contact device. Then there would be no type inversion and when it became relaxation-like there would be no far end effects. However this would imply a larger full depletion voltage V_d, due to a larger n_{eff} at a given fluence Φ.

G Even more stability could be obtained if the material were relaxation-like initially. This can be obtained using chemical impurities such as Au or Pt which are well established as lifetime killers which create g-r centres. By good fortune there is good evidence that they also reduce the values of β and α.[12].

H For any design of device we need to reduce n_{eff} in order to reduce the voltage and current at full depletion. There is a possibility of a form of auto compensation as the material goes relaxation-like.

Consider P-type material. When it starts it is lifetime-like with the Fermi energy near the valence band and all the shallow acceptors ionised and negative. When it becomes relaxation-like the Fermi energy moves to mid gap. Even deep acceptors are now ionised and negative. The same is true with the donors. As we irradiate the material it becomes more P-like, but it also becomes relaxation-like. We can make it less P-like if

we have some deep donors present. These will become ionised as the Fermi energy moves and will compensate the acceptors.

I The Charge Collection Efficiency (CCE) needs a minimum of high fields to separate the charge. Then there is a reduction due to trapping and recombination. These depend on the density and cross-section of the traps and centres for the relevant carriers and processes.

Even though relaxation material has an efficient g-r process the recombination will be small if

transit time < recombination time,

For trapping to be negligible we need

trapping time > transit time

or

detrapping time < trapping time < transit time.

J Another strategy which could be adopted with detectors is to 'sensitise' them before the signal arrives. This would need the sample state and bias to settle down before the signal and the sensitive state to last and be stable for long enough. It may be that a DC light may improve the performance since it is found that the photogeneration adds to the thermal g-r processes to give an effect as if the sample were more relaxation-like.

Sensitisation could be done with a forward bias which fills all the traps in the 'depleted region'. A light pulse creates electron-hole pairs in a surface layer for above bandgap light and empties some traps for subbandgap light. The behaviour is not easy to predict.

More details of the arguements are given in our publications [14-20].

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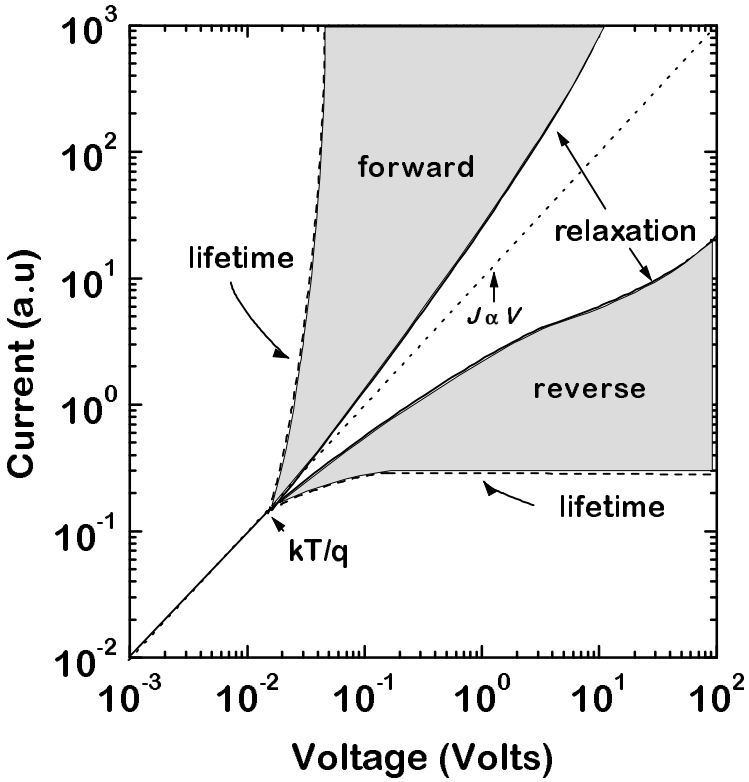

Fig. 1(a) Any real current-voltage curve for positive and reverse bias will lie within the shaded regions limited by the two regimes. The lifetime regime is represented with dashed lines and the nearly ideal relaxation limit with solid lines (After Döhler and Heyszenau[13], 1975. "*Conduction in the relaxation regime"*, Phys.Rev.B, **12**, 1975, 641).

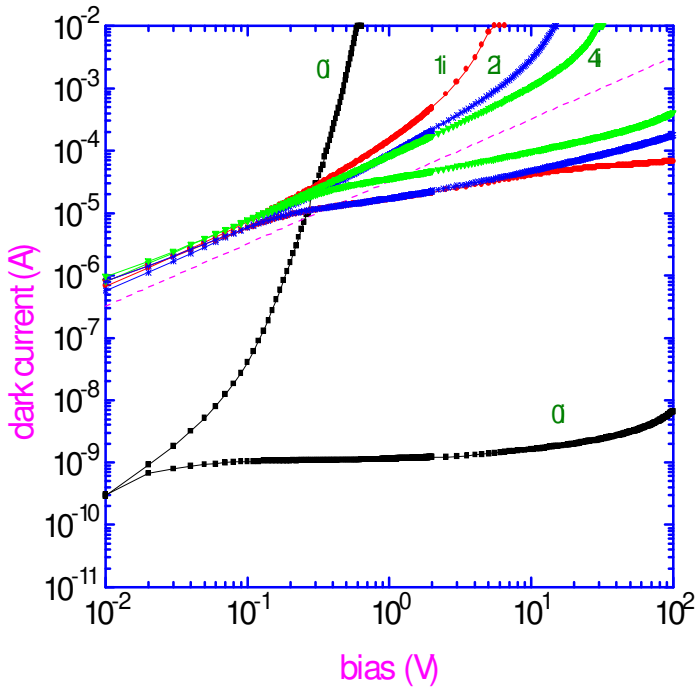

Fig 1-B: *The I-V characteristic for the CSD devices at different fluences in reverse bias and in forward bias. The theoretical maximum resistivity is shown as a dotted line.*

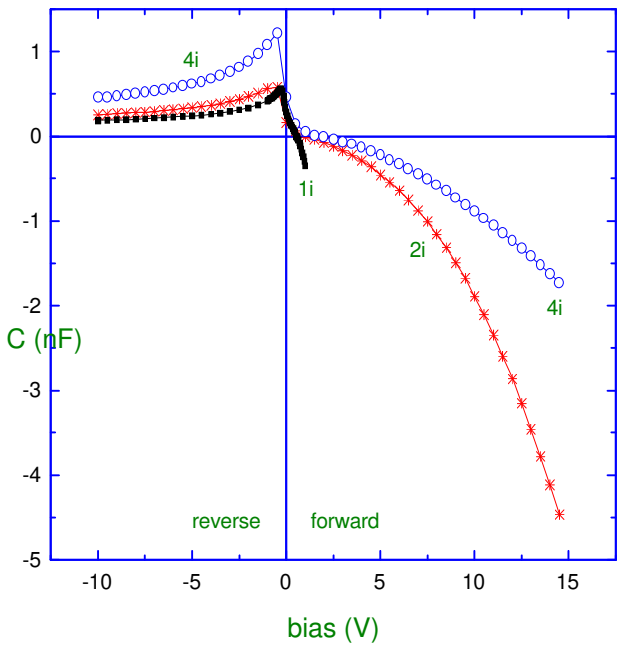

Fig 2. : The low frequency C-V characteristic for silicon diodes of increasing fluence (1,2,4) at 300 K and 10 kHz.

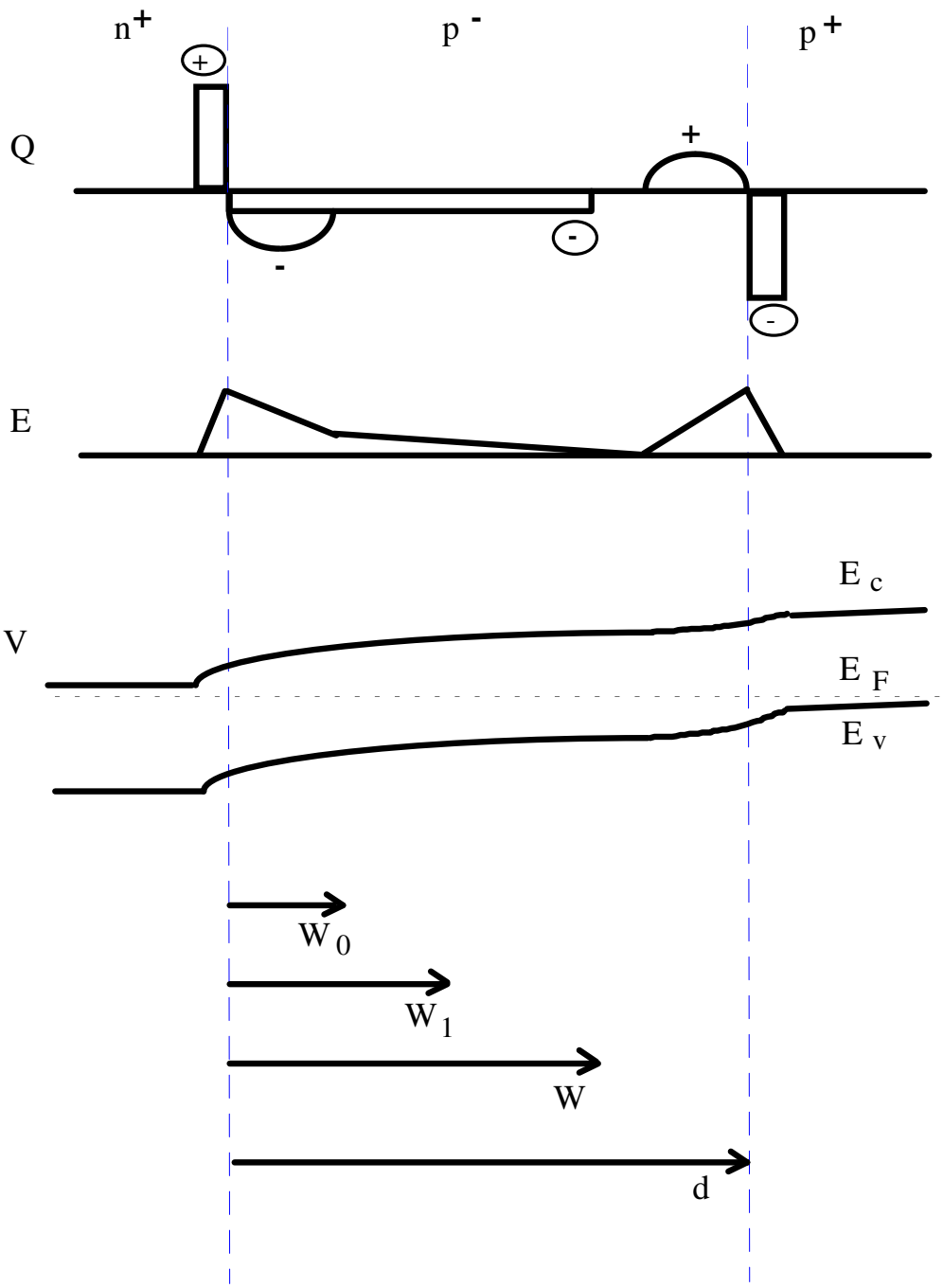

Fig 3 : Band diagram showing the distribution of the space charge density and the electric field, the band bending and the respective depletion widths.

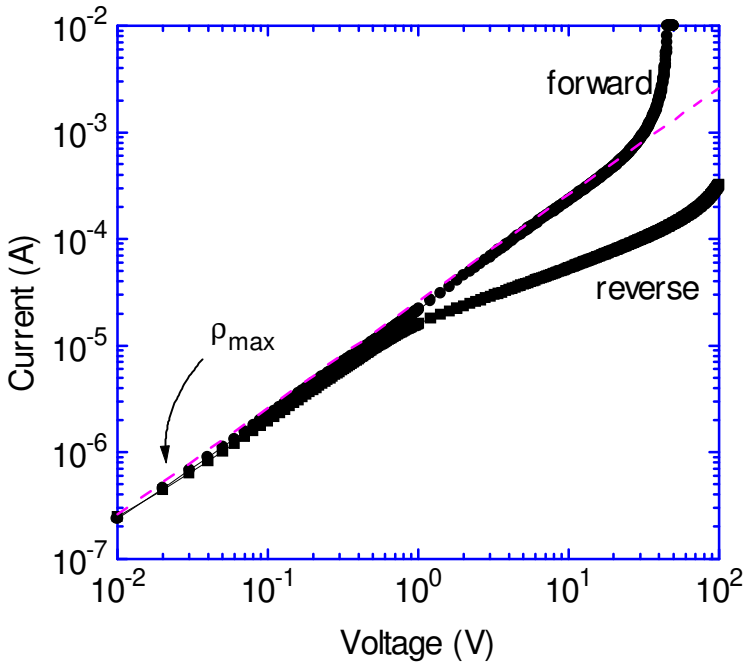

Fig. 4. Ohmic and $V^{1/2}$ regions in the I-V data for an irradiated silicon diode.

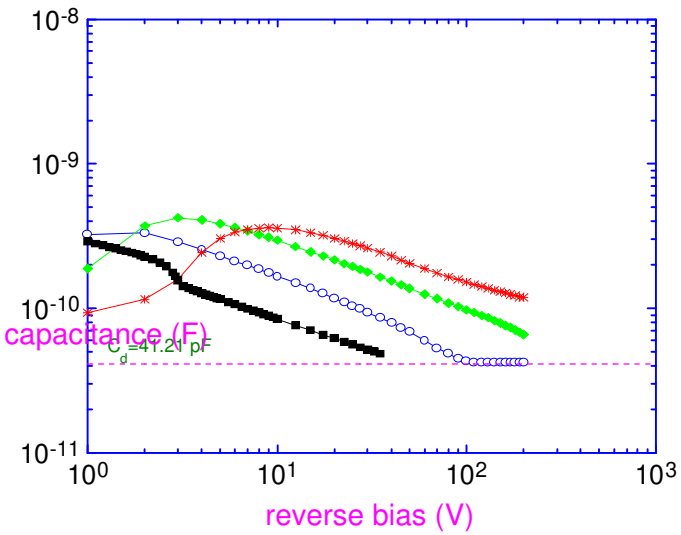

Fig 5(a) : A log-log plot of the uncorrected C-V data for silicon diodes irradiated at different fluences.

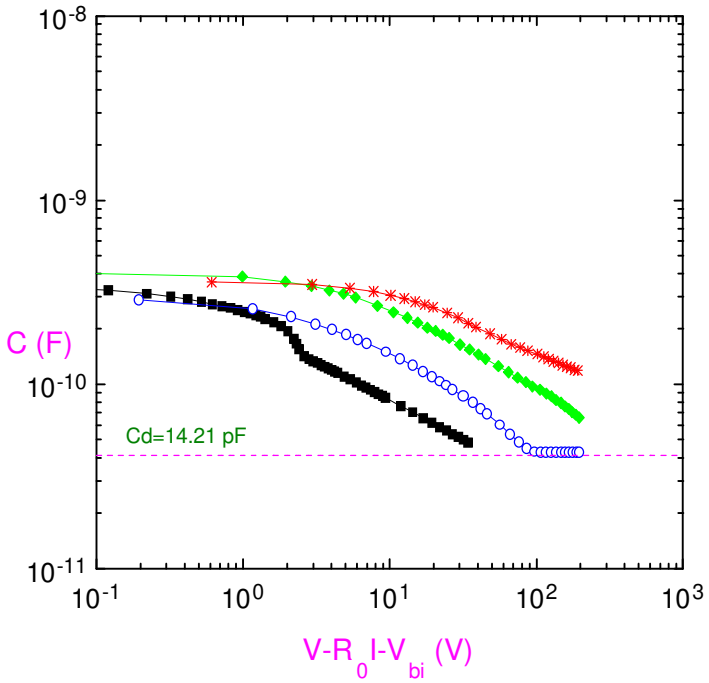

Fig 5(b) A log-log plot of the corrected C-V data for silicon diodes irradiated at . different fluences .

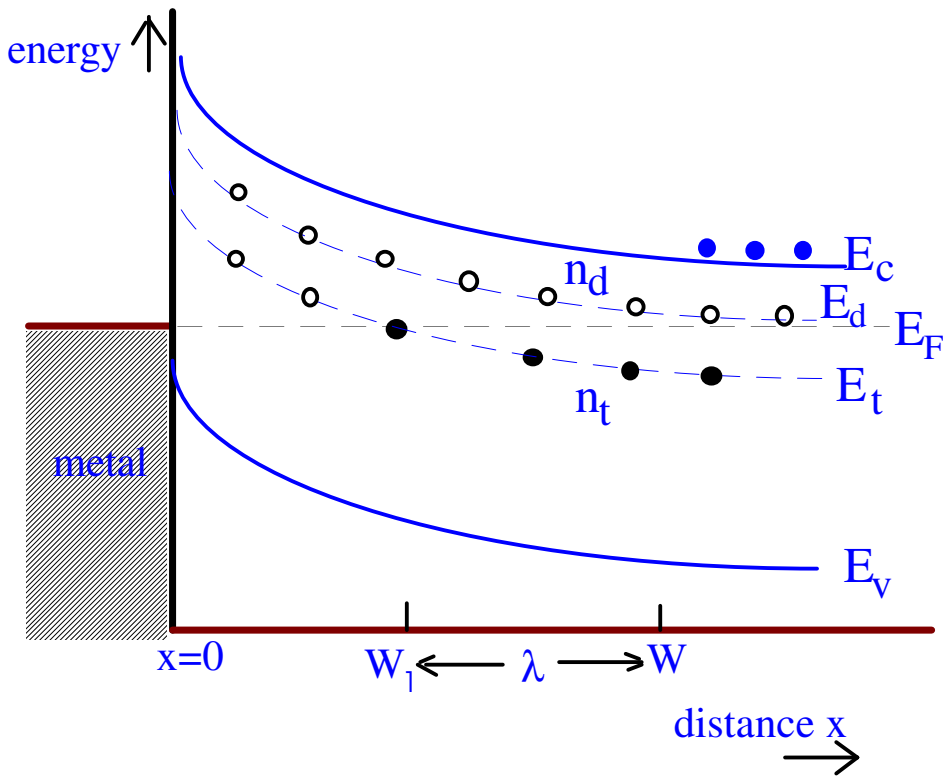

Fig 6 : Schematic energy band diagram of a Schottky barrier diode on an n-type semiconductor with traps. At the Fermi level emission occurs, above the Fermi level the traps or donors are empty and below they are full.