ROSE/TN/98-1
March 1998

Forward Bias I–V Characteristics for Heavily Irradiated Silicon Diodes

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Abstract

For future applications of irradiated Si particle detectors operating in forward bias mode the behaviour of the current as a function of bias must be better understood. A study has been made for neutron irradiated diodes and it was found that standard theory for non–irradiated diodes cannot be extended to the heavily irradiated case. Results of an empirical parameterisation are presented here, as well as an investigation of how the I–V changes with fluence between (1-10) x 10^{14} n cm^{-2} and temperature in the range 244–273K.

1 Introduction

Our previous work [1] with heavily irradiated silicon diodes has shown that they may be operated under forward bias as detectors for minimum ionising particles, with a possibility to reach a charge collection efficiency (CCE) of $\sim$ 70% at 10 times lower bias voltage than that required for a similar CCE in reverse bias operation. If forward bias mode is to be considered as a real option in future detector applications [2] then a deeper knowledge of diode behaviour under these conditions is crucial. Maximum forward bias voltage for a diode is limited by the large current, which steeply increases with voltage. This current not only increases the noise in the detector electronics, but may also cause thermal runaway. It was also noted that a study of the forward bias current–voltage (I–V) characteristics may give information on the nature of the radiation damage in Si [3].

We will investigate here I–V characteristics for both non–irradiated and heavily irradiated diodes. Results for moderately–doped semiconductor devices before irradiation will be compared with standard theory for this type of device, and an empirical parameterisation will be made for the heavily irradiated diode characteristics. Finally, a study of temperature and fluence dependence of the components of the parameterisation is presented.

2 Experimental Details

The test diodes were p-i-n diodes with 5 x 5 mm^2 sensitive area and $\sim$ 300 μm thickness, manufactured by ITE, Canberra and SINTEF for ROSE. They were irradiated at ISIS (Rutherford Appleton Laboratory) by neutrons with $\sim$ 1MeV energy to fluences (ϕ) in the range (1-10) x $10^{14} cm^{-2}$. Diodes were monitored during the beneficial annealing process, and I–V characteristics were recorded once the depletion voltage had reached a minimum value.

The current through the centre of the diode (excluding guard ring current) was measured using a Philips multimeter PM2525. The local temperature of the diode was controlled using a Melcor SealTEC ST1.4-127-045L Peltier device. The non-irradiated diode was tested at 244K (the lowest possible with water-cooling of the Peltier device) and all irradiated diodes were cooled typically to 249K for testing, in either case to reduce to the lowest level the large currents expected in forward bias mode.

3 Results and Discussion

3.1 I–V Characteristics for Non–Irradiated Diodes

Standard device theory for a moderately-doped semiconductor p-n junction diode operating in forward bias mode [4] predicts that the current through the bulk is given by:

$$I = I_0 \exp\left[\frac{V - IR_s}{V_0}\right] \tag{1}$$

where R_s is a series resistance, and V_0 and I_0 are voltage and current scaling factors. For practical purposes it is convenient to fit V as a function of I,

$$V = V_0 \ln\left(\frac{I}{I_0}\right) + IR_s \tag{2}$$

Measurements for a non–irradiated (SINTEF) diode yield a typical I–V curve, and the data are fitted with equation 2 in fig.1. The voltage factor V_0 may be expressed as,

$$V_0 = \frac{\eta k T}{q} \tag{3}$$

where q is the electron charge and η is the ideality factor, expected to be 1 for an ideal device. For this diode $\eta = 1.26$.

From the fit we find I_0=0.85nA, and R_s=360Ω. By comparison with the expectation we can attribute around 50% of this value for R_s to the diode bulk, the remainder being accounted for by the non-ideality of the backside contact.

3.2 I–V Characteristics for Irradiated Diodes

After irradiation by (1-10) x 10^{14} n cm^{-2}, the diodes may be biased at up to 200 times higher voltages, although the general shape of the I–V remains the same. Attempts were made to fit data from irradiated diodes with equation 2, and typical results can be seen in figure 2. The fit quality is rather poor.

As an alternative to this theory we endeavoured to find the best empirical description that would fit all of our available data. We assumed that the exponential dependence of I versus V still holds for the irradiated diodes, though the physical origin of this behaviour may be different from that for the non-irradiated diode. Our first attempts to fit the data used a linear term in the exponent, but this failed to give a good fit. We then used a combination of linear and quadratic terms in the exponent and discovered that the linear term was unnecessary for good fitting. At low voltages the diode behaves like a resistor, and we have included a term linear with voltage that describes this. The result was the parameterisation:

$$I = I_0 \left[\exp \left(\frac{V}{V_1} \right)^2 - 1 \right] + G_0 V \tag{4}$$

where G_0 is a conductance term, and I_0 and V_1 are respectively current and voltage scaling factors. Fitting forward bias I–V for non-irradiated diodes with this function gave a poor result and it was obvious that the data were described better by equation 1. In figures 3 a,b,c are seen data for diodes irradiated by 0.93, 2.2 and 9.8 x 10^{14} n cm^{-2}, fitted by equation 4. The lines in all figures presented for the I–V data are solid in the range used for the fit and dotted outside of the fit range. In a study of all of our data for irradiated diodes we find that this equation gives the best fit subject to 2 conditions:

(i) V_{bias} remains less than $1.5V_1$

(ii) Power dissipation in the diode does not exceed $\sim 10mW$

When either of these conditions fails to be met, the measured current at these highest voltages is larger than the value expected from the fit. Figure 4 is an illustration of these requirements. V_{max} is the value of V_{bias}, and W_{max} is the power dissipation, in the last point which was fitted by equation 4. We see that the ratio $\frac{V_{max}}{V_1}$ is never much more than 1.5. For large values of V_1 the limit is set by power dissipation at about 10mW level. When neither of limits (i) or (ii) were reached in the data we were able to fit all the I–V data points for such a diode. These cases are shown in figure 4 by solid squares.

The fit quality was characterised by the value of χ^2 with the error in current measurement set at the multimeter resolution of $0.1\mu A$. The fit was considered to be good if the value of $\frac{\chi^2}{N_{df}}$ (where N_{df} is the number of degrees of freedom) did not exceed 2. Typically $\frac{\chi^2}{N_{df}}$ increased very rapidly when the points not satisfying conditions (i) or (ii) were included into the fit.

3.3 Temperature Dependence of Forward Bias I–V for Irradiated Diodes

One diode irradiated by 9.8 x 10^{14} n cm^{-2} was investigated at 5 temperatures in the range 244–273K, see figure 5. There is an obvious tendency for I to increase with temperature at any given bias voltage but the shape of the curve is nearly the same. Figures 6 a,b,c show how well the data were fitted by equation 4 at 244, 257 and 273K.

The variation of the fitted parameters I_0, G_0 and V_1 with temperature are shown in figures 7, 8 and 9. The scaling parameter V_1 is found to decrease with a slope $\sim 2\%K^{-1}$ at ~250K. The conductance parameter G_0, and the current scaling factor I_0 show exponential dependences,

$$G_0, I_0 \sim \exp\left(\frac{-E_a}{kT}\right) \tag{5}$$

with $E_a = (0.564 \pm 0.002)$eV for G_0 and $E_a = (0.238 \pm 0.021)$eV for I_0.

3.4 Fluence Dependence of Forward Bias I–V for Irradiated Diodes

Forward bias I–V was measured at 249K for diodes irradiated to fluences in the range of (0.93-9.8) x 10^{14} n cm^{-2}, and figure 10 shows how the characteristics change at 4 different fluences. For typical fits with equation 4 refer to figure 3.

Table 1: Parameter Summary

Parameter	ϕ dependence at 249K	Temperature dependence
ρ_0, MΩ cm	35.1 independent of ϕ	$\exp\left(\frac{+0.564eV}{kT}\right)$
I_0, μA	$9.8{+}1.6\left(\frac{\phi}{10^{14}}\right)$	$\exp\left(\frac{-0.238eV}{kT}\right)$
V_1, V	$13.73\left[\left(\frac{\phi}{10^{14}}\right)-0.49\right]$	weak, $\sim 2\% K^{-1}$at $\sim$250K

Figures 11, 12, and 13 show the variations in the fit parameters with fluence. We have converted G_0 to the specific resistivity ρ_0 (where $\rho_0 = \frac{Area}{G_0 * width}$), and it is seen to be almost independent of ϕ in this fluence range (figure 11). The $\rho_0(249K)$ has a relatively large spread of σ=11.0MΩcm. Its average value $\langle\rho_0(249K)\rangle$ of 35.1MΩcm is comparable with the intrinsic resistivity for non-irradiated silicon of $\rho_{intrinsic}(249K)$ = 23.0MΩcm [5]. At this temperature parameter I_0 grows with fluence approximately as,

$$I_0(\mu A) = 9.8 + 1.6\phi \tag{6}$$

where ϕ is in units $10^{14}cm^{-2}$. Both ρ_0 and I_0 are corrected to the temperature 249K using equation 5. V_1 at the same temperature can be fitted by a linear function of fluence with much better accuracy,

$$V_1(volts) = 13.73(\phi - 0.49). \tag{7}$$

Table 1 summarises all of the results for parameter dependences on fluence and temperature.

4 Conclusions

Standard theory describing I–V characteristics of moderately–doped semiconductors in forward bias mode describes the behaviour of our diodes before irradiation very well. This theory can not however describe diodes after irradiation by neutrons to fluences in the range (1-10) x 10^{14} n cm^{-2}. Instead, the data were fit empirically with the parameterisation,

$$I = I_0 \left[\exp\left(\frac{V}{V_1}\right)^2 - 1 \right] + G_0 V$$

and it is found that this applies in the range where $V < 1.5V_1$, and where power dissipation does not exceed $\sim 10mW$. However, this was found not to fit our data for non–irradiated diodes. The conductance parameter G_0 and current scaling factor I_0 grow with temperature with an exponential dependence,

$$I_0, G_0 \sim \exp\left(\frac{-E_a}{kT}\right)$$

while V_1 decreases with temperature more weakly. Note that $V_0 = \frac{\eta kT}{q}$ grows linearly with temperature.

At a measurement temperature of 249K, both I_0 and the voltage scaling factor V_1 can be seen to increase significantly with fluence, but ρ_0 is practically constant over this fluence range with an average value comparable with $\rho_{intrinsic}$ at the same temperature.

Acknowledgements

The authors would like to thank Brian Jones and Michael McPherson for their helpful discussions.

References

[1] Chilingarov, A and Sloan, T:*Operation of Heavily Irradiated Silicon Detectors under Forward Bias*, Nucl. Instr. and Meth. A399 (1997) 35-37

[2] Sicho et al: *Measurements Properties of Highly Irradiated p+n Pixel Detector Structures*, ATLAS INDET-NO-189, November 1997

[3] M Solanky: *Forward Characteristics and DLTS Study of Different Material*, talk presented at 3rd ROSE Workshop, DESY, Hamburg, 12-14 February 1998.

[4] Sze, S M:*Physics of Semiconductor Devices*, Wiley InterScience, New York, 1969.

[5] Chilingarov, A:*Semiconductor coordinate detectors in elementary-particle physics*, Sov. J. Part. Nucl. 23 (3), May–June1992, p348.

Figure Captions

Fig. 1. I–V for a non–irradiated diode. The line is a fit by equation 2.

Fig. 2. I–V for a diode irradiated by 9.8 x 10^{14} n cm^{-2} with the best fit using equation 2, which is a good representation of the data for non-irradiated diodes (see fig 1).

Fig. 3. (a) I–V for a diode irradiated by 0.93 x 10^{14} n cm^{-2}
(b) I–V for a diode irradiated by 2.2 x 10^{14} n cm^{-2}
(c) I–V for a diode irradiated by 9.8 x 10^{14} n cm^{-2}
The lines are the fits by equation 4.

Fig. 4. $\frac{V_{max}}{V_1}$ versus W_{max}. Solid symbols correspond to the cases when all available points were included in the fit. See text for further details.

Fig. 5. I–Vs for one of the diodes irradiated by 9.8 x 10^{14} n cm^{-2} measured at various temperatures in range 244–273K.

Fig. 6. I–V for diode irradiated by 9.8 x 10^{14} n cm^{-2} at
(a) 244K (b) 257K and (c) 273K.

Fig. 7. V_1 versus T for the diode irradiated by 9.8 x 10^{14} n cm^{-2}.

Fig. 8. G_0 versus T for the diode irradiated by 9.8 x 10^{14} n cm^{-2}.

Fig. 9. I_0 versus T for the diode irradiated by 9.8 x 10^{14} n cm^{-2}.

Fig. 10. I–V at 249K for diodes at different fluences between 1-10 x 10^{14} n cm^{-2}.

Fig. 11. ρ_0 versus fluence at 249K for the irradiated diodes, together with a linear fit.

Fig. 12. I_0 versus fluence at 249K for the irradiated diodes, together with a linear fit.

Fig. 13. V_1 versus fluence at 249K for the irradiated diodes, together with a linear fit.

Figure 1. I-V for a Non-Irradiated Diode

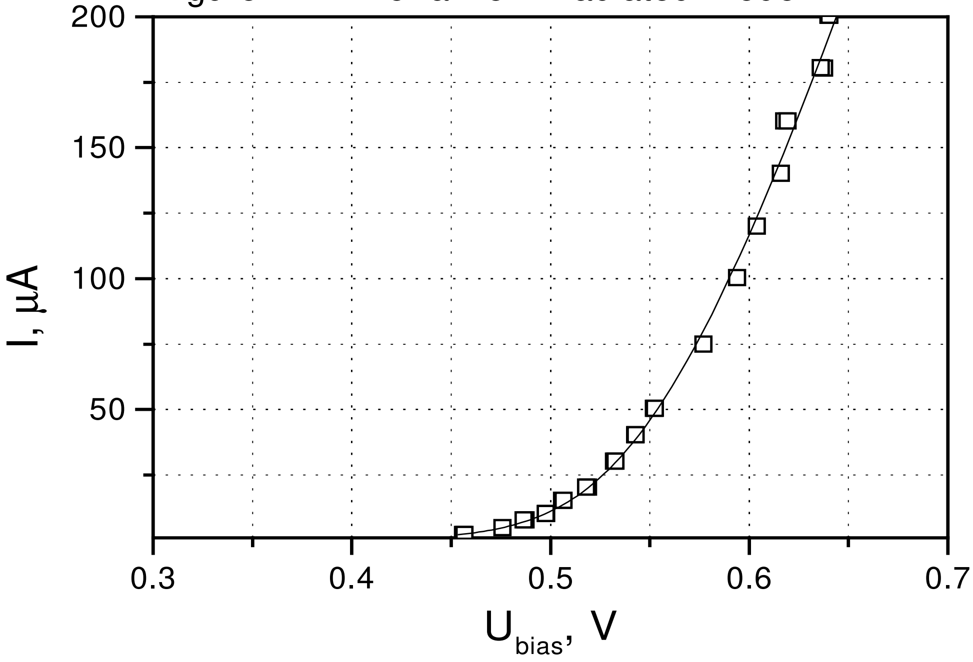


Figure 2. I-V for a Diode irradiated by 9.8×10^{14} n cm^{-2}

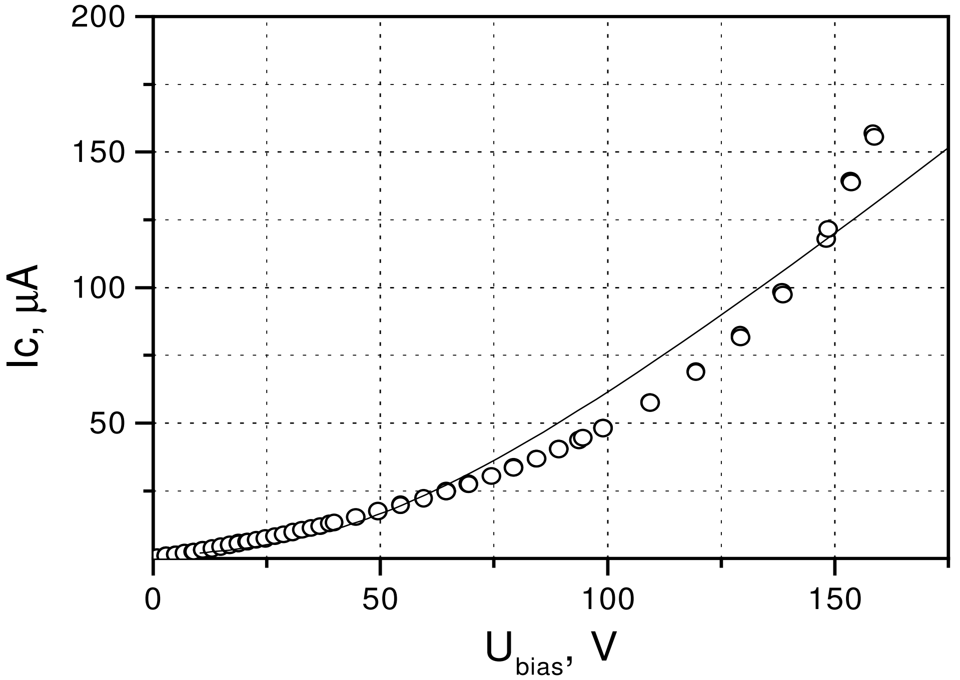
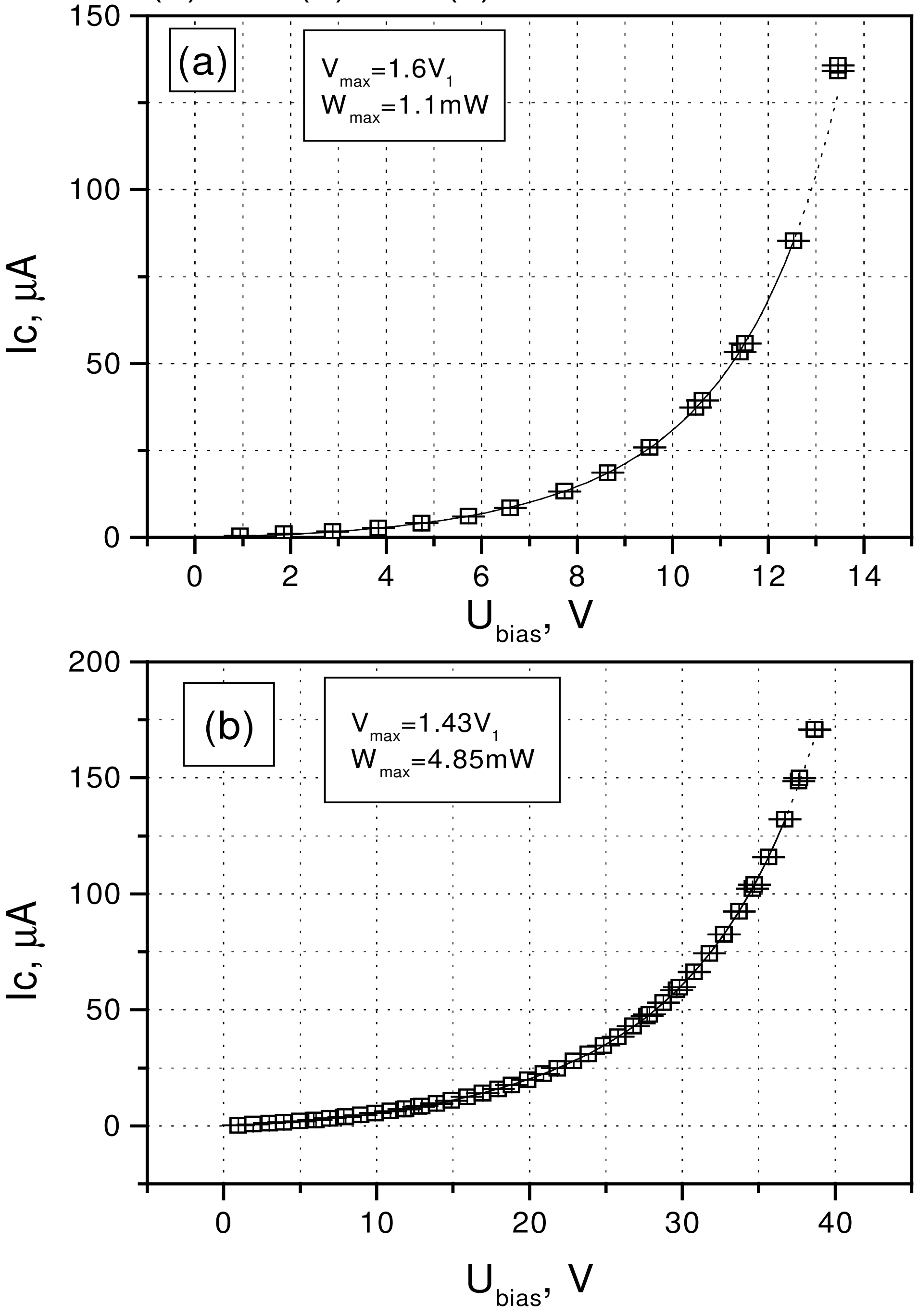


Figure 3. I-V for diodes irradiated by (a) 0.9, (b) 2.2, (c) 9.8 x 10^{14} n cm^{-2}



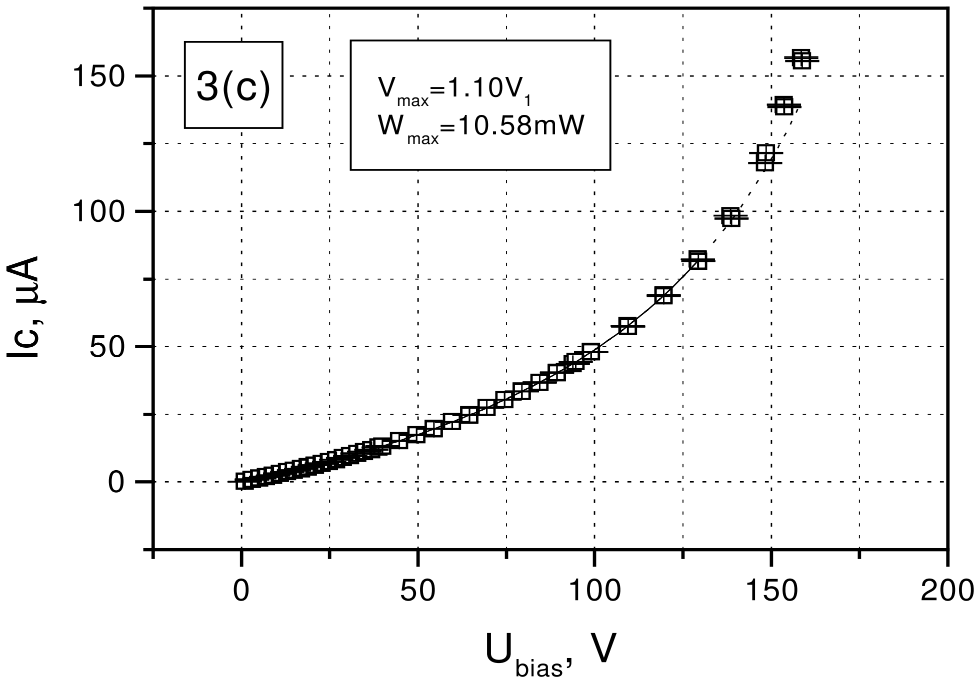


Figure 4. V_{max}/V_1 versus W_{max}

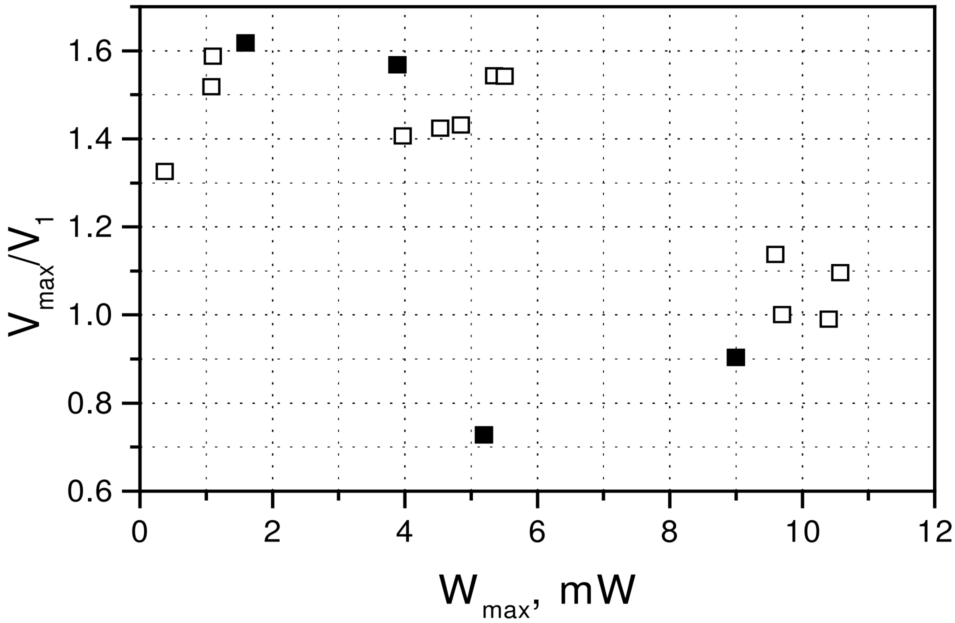


Figure 5. I-Vs for an Irradiated Diode measured at 244-273K

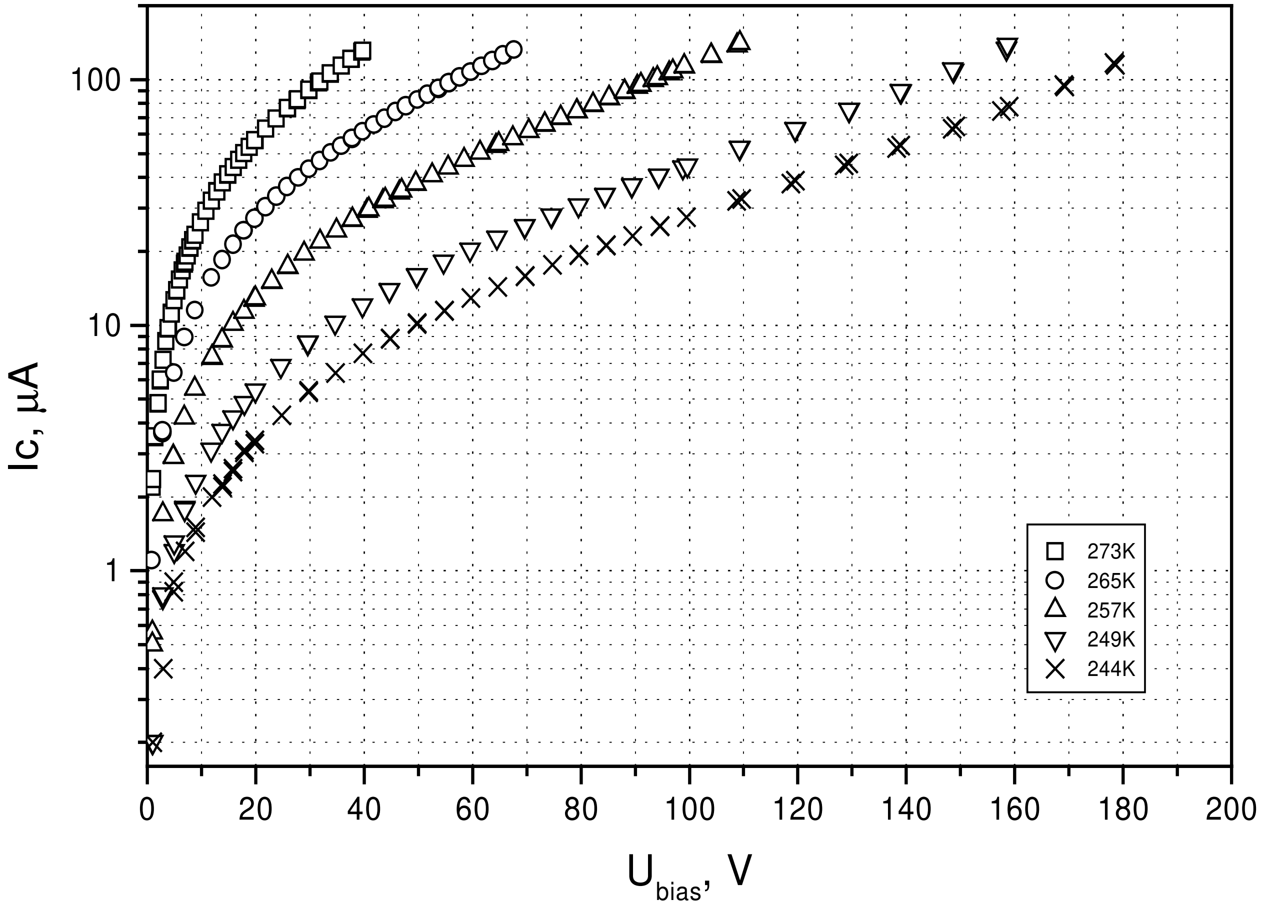
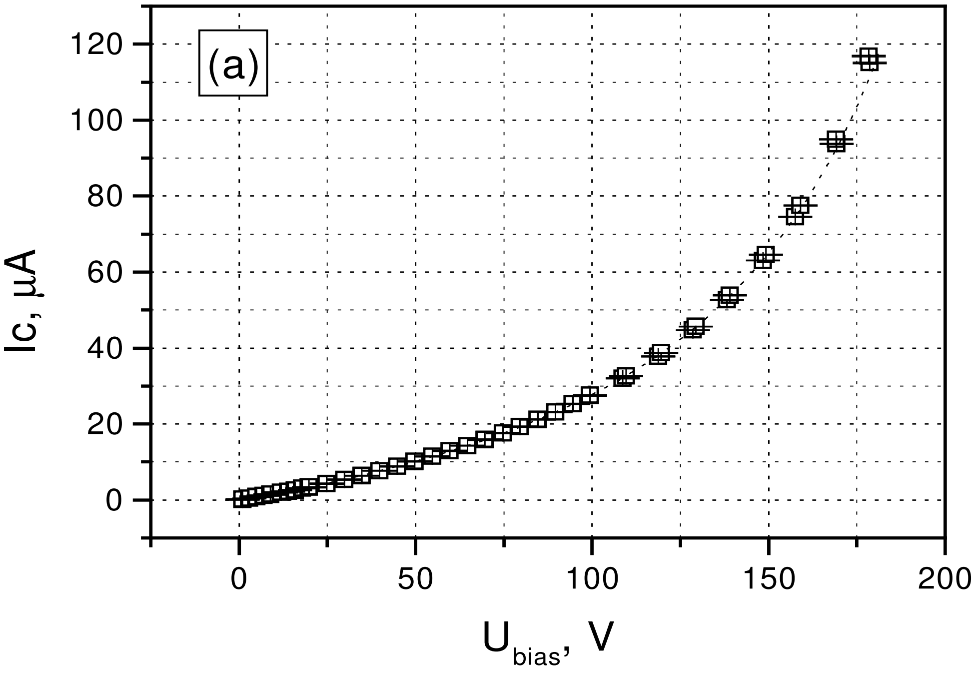
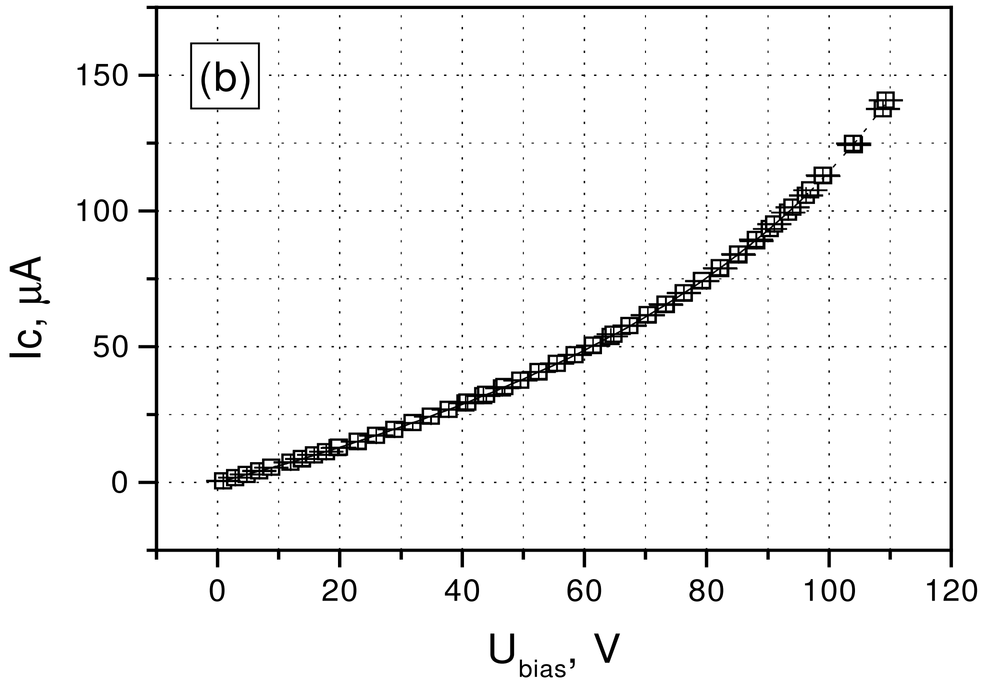


Figure 6 I-V for diode irradiated by 9.8×10^{14} n cm^{-2}
(a) at 244K, (b) at 257K, (c) at 273K





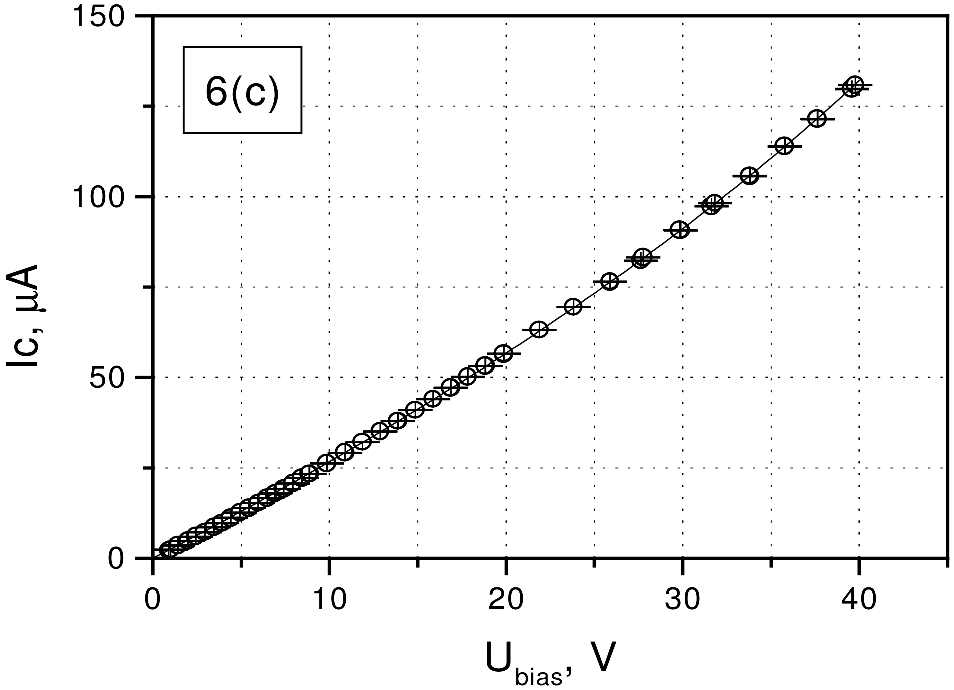

6(c)
Ic, μA
150
100
50
0
0
10
20
30
40
U_bias, V

Figure 7. V_1 versus T

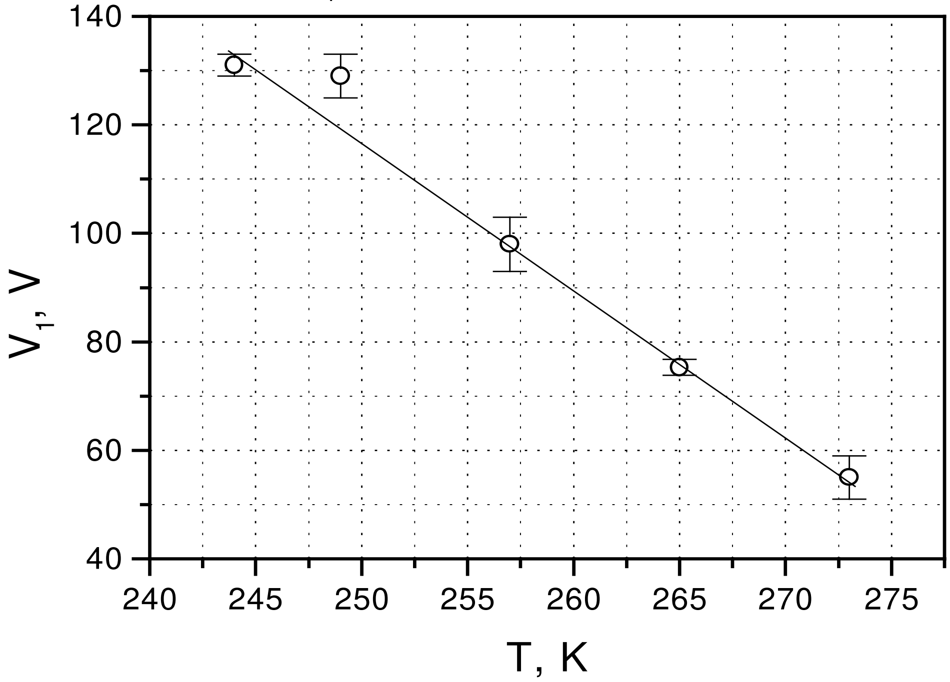


Figure 8. G_0 versus T

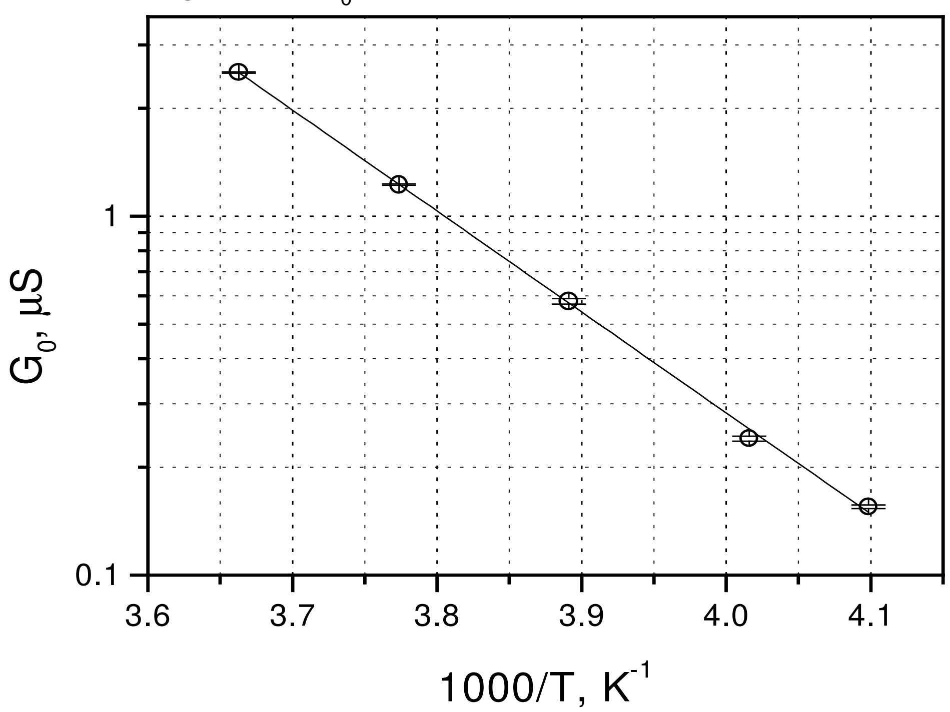


Figure 9. I_0 versus T

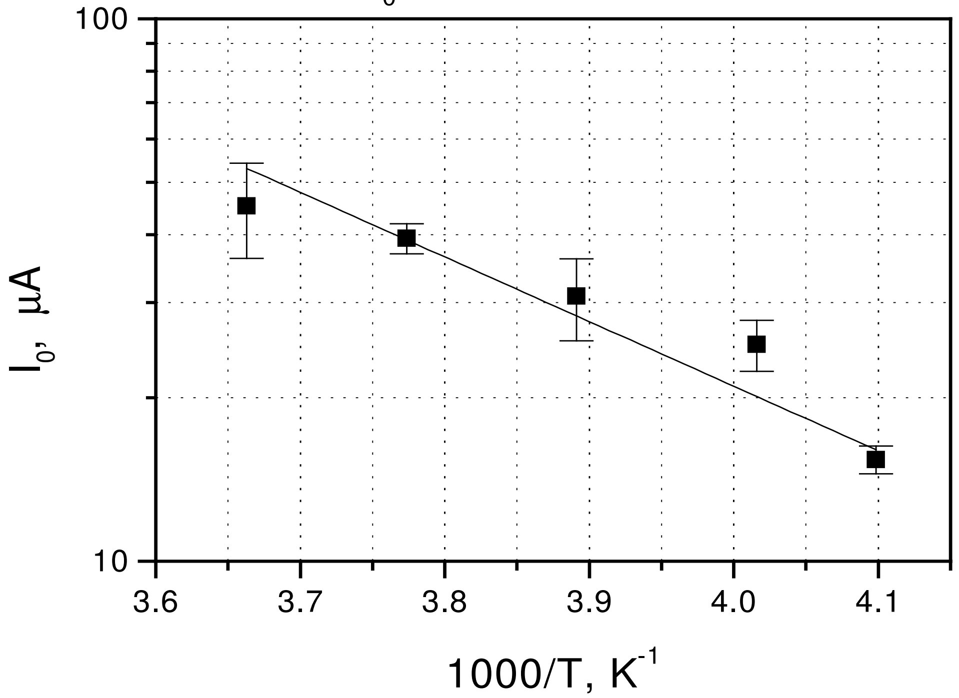


Figure 10. I-V at 249K for diodes irradiated by 1.1-9.8 x 10^{14} n cm^{-2}

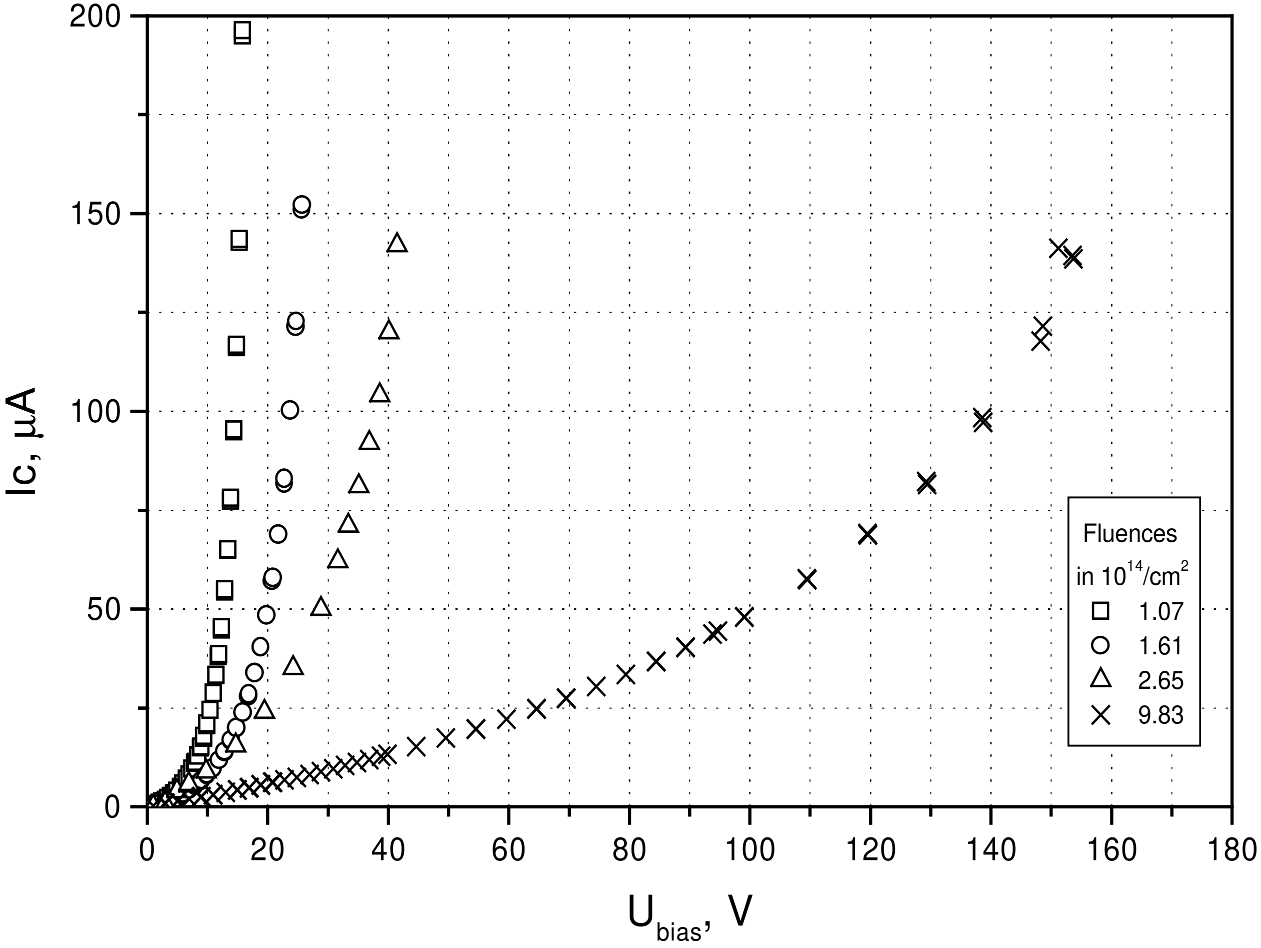


Figure 11. ρ_0 versus ϕ at 249K

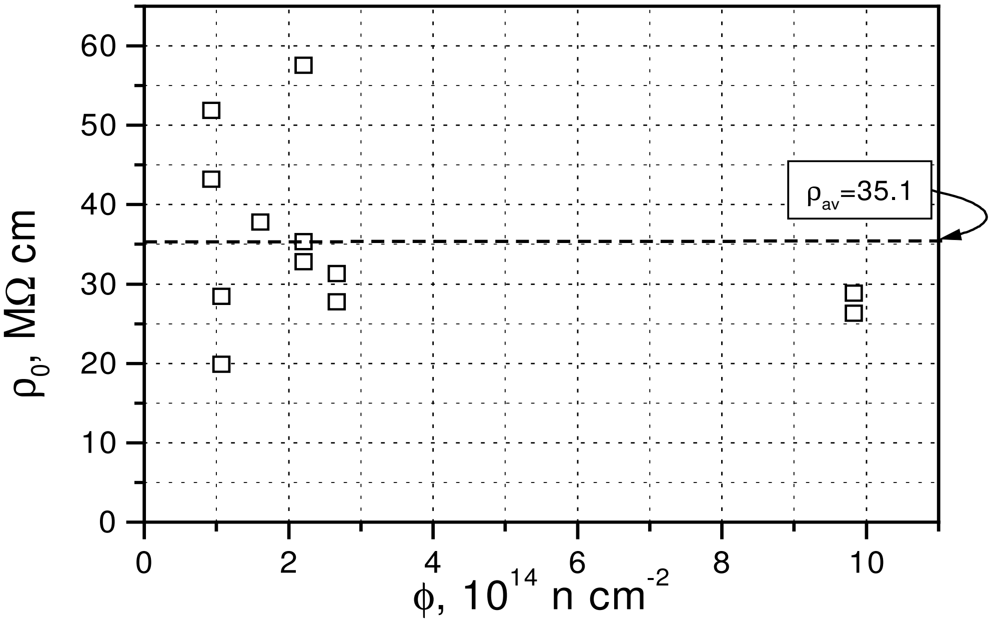


Figure 12. I_0 versus ϕ at 249K

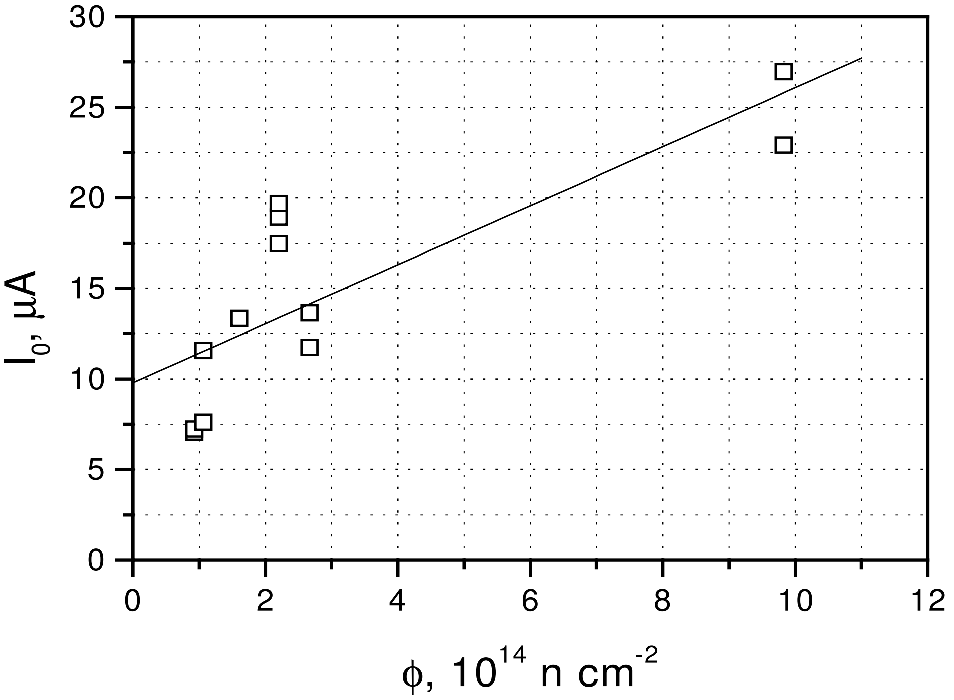


Figure 13. V_1 versus ϕ at 249K