Infrared Physics Vol. 19, pp. 185 to 189
© Pergamon Press Ltd 1979. Printed in Great Britain
0020-0891/79/0301-0185$02.00/0

ION IMPLANTATION AND DEPLETION IN GERMANIUM AT LOW TEMPERATURES

S. A. EL-ATAWY, P. E. CLEGG and D. W. PALMER[1]

Physics Department, Queen Mary College, Mile End Road, London E1 4NS, U.K., and
[1]School of Mathematical and Physical Sciences, University of Sussex, Brighton BN1 9QH, U.K.

(Received 23 October 1978)

Abstract—Radiation and d.c. characteristics of surface implanted *n*-type Ge were investigated at liquid helium temperatures. A thin *p*-type degenerate layer was formed by boron implantation on an *n*-type bulk crystal. The depletion depth of free carriers in the *n*-type crystal caused by the formed *p–n* junction was estimated, and the effect of such depletion on the *n*-type bulk absorption of submillimetre radiations was studied.

1. INTRODUCTION

In the course of a programme of improving the submillimetre performance of liquid-helium-cooled Ge bolometers we have investigated ion-implantation of the surface. Our aim has been to produce surface layers which would be matched to free space electromagnetically and matched to the germanium substrate thermally (acoustically), so as to maximise the bolometric response to an incident signal. The results of implantation were less simple than we had anticipated and more has to be done to obtain a major improvement in detector performance. However, we report here briefly on the depletion effects because we feel they may have significance in the wider context of the development of semiconductor devices for operation at liquid-helium temperatures.

2. SAMPLE PREPARATION

Samples were prepared from Ge crystals containing Sb at a concentration of about $5.5 \times 10^{16}\,cm^{-3}$. A 12 mm diameter circular disc was cut from a single crystal grown in the [110] direction. The disc was finely polished and etched for about 1 min in CP4A solution (Nitric, hydrofloric and acetic acids + bromine). It was then surface-implanted* at room temperature by 60 keV boron ions B^+ to a dose of 3×10^{14} ions per cm^2, forming a *p*-type layer(1) with thickness of about 0.2 μm with surface sheet resistance of $209 \pm 10\,\Omega/\square$. The doping level of this *p*-type layer ($\sim 1.5 \times 10^{19}\,cm^{-3}$) lies in the metallic region of conduction where the resistance should not vary strongly with temperature. The sheet resistance was measured at the pumped-helium temperature of 1.5 K, and no difference was observed from its value at 300 K.

After the optical transmission measurements were taken, as described below, $4 \times 2 \times 0.25\,mm^3$ samples were cut from the disc for bulk resistance measurements at 4.2 and 1.5 K. The edges of these elements were etched to prevent surface leakage currents between the degenerate layer and the bulk material, to which electrical contacts were then made.

3. D.C. PROPERTIES AT LOW TEMPERATURES AND THE FORMATION OF A P–N JUNCTION

The low temperature conductivity, σ, of Ge doped in the range $1.5–8 \times 10^{16}\,cm^{-3}$ shows three distinct thermal activation energies:

$$\sigma = \sum_{i=1}^{3} \sigma_i \exp\frac{-\epsilon_i}{kT}. \quad (1)$$

* We wish to thank the Philips Research Laboratory, Redhill, U.K., for the implantation.

This is in contrast to lower doping concentrations where only ϵ_1 and ϵ_3 are seen. ϵ_1 arises from excitation from the donor states to the conduction band whilst ϵ_3 is believed to be associated with a ground-state hopping between donors in the presence of some compensating impurities.[2-4] We believe ϵ_2 to arise from thermal excitation from the ground state to an intermediate impurity band lying between the ground state and the continuum conduction band.[5,6] Hall-effect measurements have shown that the mobility of carriers in this impurity band is less than in the conduction band, but greater than for hopping carriers, and at 4.2 K the impurity band carriers dominate the conduction mechanism. At temperatures <2.7 K, nevertheless, the hopping process dominates because of the greater excitation energy of the impurity band.

Figure 1 shows the logarithm of the resistance of a typical element plotted against the logarithm of the applied voltage at temperatures of 4.2 and 1.5 K. Similar curves for an unimplanted specimen are shown for comparison. It will be seen that, for low voltages, the degenerate layer does not short out the bulk crystal—indeed, the resistance of the implanted sample is higher than that of the bulk and we attribute this to the formation of a depletion layer and the consequent confinement of the current to a thin conducting channel. At 4.2 K there is, furthermore, a sudden increase in resistance around 0.1 V which is probably caused by the pinching-off of this channel at the positive end of the strip. We now discuss these effects more quantitatively.

Implantation of an n-type sample with B creates a p–n junction and therefore a depletion layer is created whose depth in the n-type material is, in general, given by

$$H = \left(\frac{2\epsilon\phi}{en}\right)^{1/2} \tag{2}$$

where ϕ is the potential across the junction, ϵ the permittivity of the material ($1.42 \times 10^{-10}\,\mathrm{Fm^{-1}}$ for Ge), e is the electronic charge and n is the *free* carrier concentration. At liquid helium temperatures, the concentrations of free carriers in the bulk material is reduced dramatically relative to the room temperature exhaustion value, and Eqn 2 shows that the depletion depth will consequently increase. The p-type implanted layer on the other hand, being degenerate, will not suffer the same carrier concentration decrease and the depletion depth will barely change.

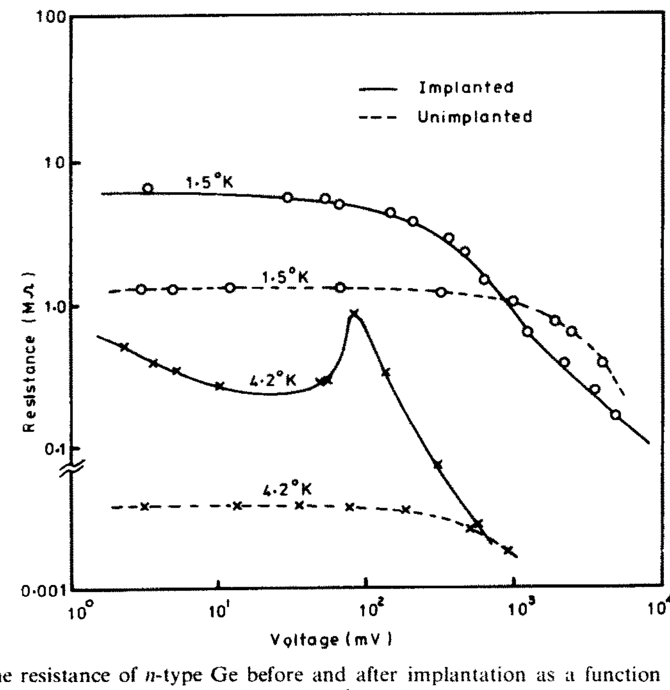

Fig. 1. The resistance of n-type Ge before and after implantation as a function of the element voltage.

Equation 2 may be rewritten to give

$$\frac{H}{H_0} = \left(\frac{\phi}{\phi_0}\right)^{1/2} \tag{3}$$

where the suffix zero denotes unbiased values, i.e. the value in the absence of applied bias voltage. If we assume a typical value of ϕ to be 0.5 V, then pinch-off at an excess potential difference of 2 × 0.05 V (Fig. 1), together with the total sample thickness of 250 μm, tells us that the unbiased channel thickness is ~ 12 μm. The implantation therefore decreases the conduction channel, from the full 250 μm, by a factor of ~20; this is confirmed by the increase in resistance of this order between implanted and an unimplanted specimen shown in Fig. 1. If we now substitute the values $\phi_0 = 0.5$ V, $H_0 = 238\ \mu$m in Eqn 2, we obtain for n_0 the value of ~ $1.6 \times 10^{10}\ \text{cm}^{-3}$. This value is much smaller than the measured impurity band concentrations of ~ $1.5 \times 10^{13}\ \text{cm}^{-3}$ but is about the right value for the conduction band concentration. In other words, the depletion depth has been formed at the expense of conduction band carriers, which is what we might expect from the Einstein relation

$$\frac{\mu}{D_c} = \frac{e}{kT}$$

between the mobility μ and diffusion coefficient D_c. (It will be remembered that the conduction band carriers have higher mobility than those in the impurity band.)

At 1.5 K, the concentration of carriers is reduced still further and, as the sample thickness is fixed, impurity band carriers must take part in the depletion in order to maintain space-charge neutrality across the junction. If we assume that the depletion depth at this temperature is about the total specimen width of 250 μm, we find the necessary depletion carrier concentration to be ~ $1.8 \times 10^{10}\ \text{cm}^{-3}$ which is equal to the measured impurity band concentration at 1.5 K, i.e. the impurity band is almost totally depleted. The consequences of this for infrared absorption are discussed below.

It might be argued that the thermal excitation of carriers at temperatures <4 K is insufficient to adjust the depletion depth to various bias values. To see whether this was the case, we subjected the junction to variable transverse bias (by applying two more contacts across the specimen) at low temperatures and checked for any hysteresis effects. None was observed.

Returning to Fig. 1, we find that at bias voltages above 0.1 V, the specimen resistance at 4.2 K drops rapidly. We attribute this to impact ionisation caused by the barrier field. We have found the same effect when attempting to reduce the sample thickness in order to reduce the thermal capacitance: The resistance of a $3 \times 3 \times 0.11\ \text{mm}^3$ sample, was found to be *less* than that of a thicker sample. We think that this is because reducing the sample thickness has the same effect as increasing the junction reverse bias as far as the internal electric field is concerned and with sufficiently thin samples, breakdown occurs. For satisfactory operation as a detector element, the bulk material must be sufficiently thick to allow operation at the bias voltages of $\gtrsim 3\ \text{V cm}^{-1}$ found optimum for unimplanted samples.

One puzzling feature of our experiments we have not explained. We measured the activation energies ϵ_2 and ϵ_3 between 4.2 and 1.5 K for both original and implanted samples and found that while ϵ_2 remained unchanged, ϵ_3 diminished from 0.9 to 0.33 meV on implantation (see Fig. 2). Models of hopping conduction[7] give for ϵ_3 the relationship

$$\epsilon_3 = \frac{e^2}{2\epsilon}(N_D^{1/3} - A\,N_A^{1/3}) \tag{4}$$

where N_D and N_A are, respectively, the donor and compensating acceptor concentrations, and A is a constant. It seems natural, therefore, to attribute the change in ϵ_3 to a change in acceptor concentration by the diffusion of B atoms during the soldering

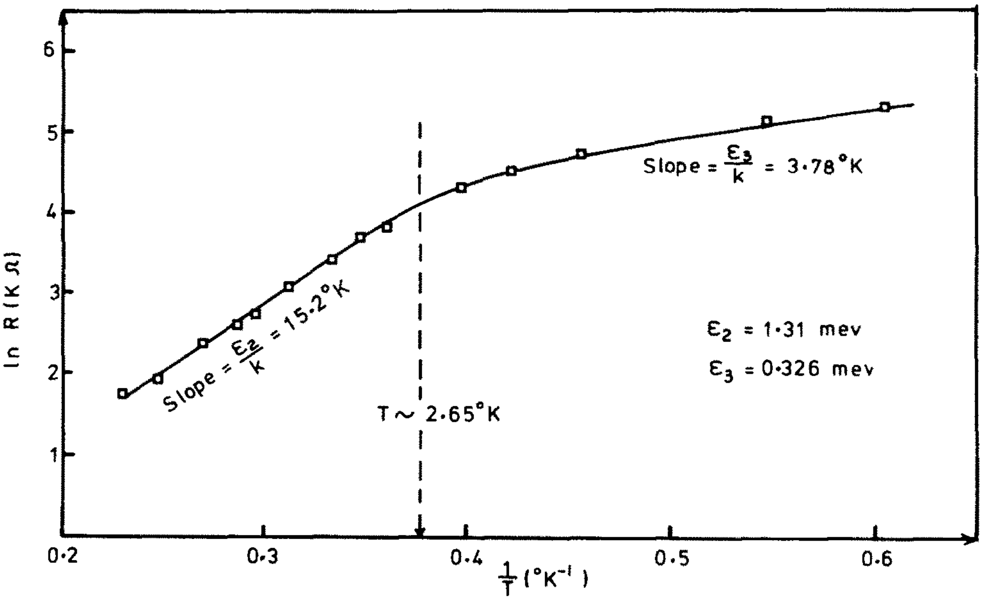

Fig. 2. The resistance of the implanted Ge as a function of reciprocal temperature.

process, for example. Calculations show that the diffusion rates are far too slow for this to occur. (The activation energy ϵ_2 depends only on donor wave function overlap and is therefore expected to remain unchanged.)

4. OPTICAL PROPERTIES

Optical transmission measurements, in the frequency range of interest—10–60 cm^{-1}—were made at 1.5 K before and after ion implantation (radiation is incident on the implanted surface). The results are shown in Fig. 3. Because the sample sides were parallel, Fabry–Perot fringes were observed at the expected frequency separation of $2n\lambda$, where n is the refractive index of the substrate and λ the free-space wavelength. For reasons to be explained below these fringes have been smoothed out in Fig. 3, fitting by eye a smooth mean curve. The curve for the unimplanted sample indicates

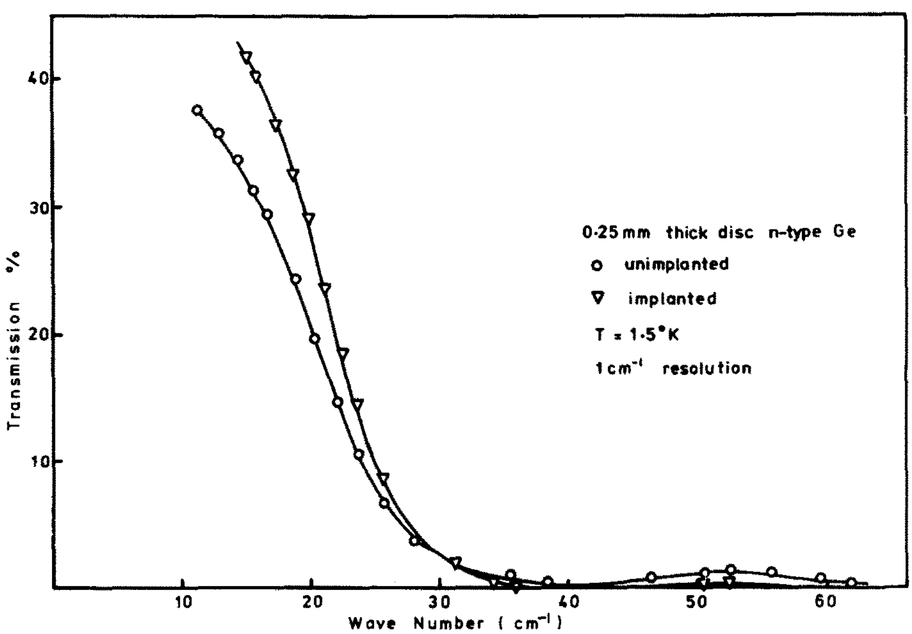

Fig. 3. Transmission spectra before and after surface implantation.

a tendency to a transmission of $\sim 40\%$ at low frequencies. For a non-absorbing, 250 μm thick slab of refractive index 4 (the value for Ge), the usual transmission-line theory[8] predicts a transmission maxima and minima of 100 and 22%, respectively. The geometric mean of this is $\sim 47\%$ in reasonable qualitative agreement with the mean curve at low frequencies. On the other hand, for a non-absorbing material this curve should be independent of frequency so that the observed curve indicates substantial absorption by the unimplanted Ge.

Application of the transmission line theory to an absorbing medium leads to a tediously complicated expression. When considering the qualitative behaviour of the implanted sample therefore we assume the implanted layer to be an infinitely thin conductor, of impedance Z_0/f, where Z_0 is the impedance of free-space, upon a substrate of impedance Z_0/n. It is because of this simplification that we do not follow in detail the Fabry–Perot behaviour of the sample. Using our values of $f = 377/209 = 1.8$ and $n = 4$ we predict maximum and minimum transmittances T of 25 and 7%, respectively. (The corresponding absorption in the film should always be fT in our arrangement and should consequently vary between 50 and 14%.) The geometrical mean transmission should therefore be $\sim 13\%$. We were somewhat disappointed therefore to find that the observed transmission of the implanted sample was always *greater* than that of the unimplanted indicating that, far from increasing the absorption, as desired, the presence of the substrate was actually decreasing it. There are aspects of this discrepancy which need explanation:

(i) Regardless of the presence of the implanted layer, we might expect the intrinsic Ge absorption to remain the same.

(ii) Regardless of the presence of intrinsic absorption, we should expect the presence of the implanted layer to increase absorption.

We believe that (i) is easily explained by the depletion of absorbing carriers in the bulk material discussed in section 4.

The explanation of (ii) we think lies in the carrier relaxation time in the implanted layer. If the lifetime is τ, then the impedance at frequency ν is given by

$$Z(\nu) = Z(0)[1 + (2\pi\nu\tau)^2] \tag{5}$$

so that at the radiation frequency the impedance of the film is not 209 $\Omega/\square$, as we had assumed, but a higher value leading to smaller absorption. We estimate a crude upper limit to the value of τ by assuming that $2\pi\nu\tau \sim 1$ at the lowest frequency measured ($10\,\text{cm}^{-1}$). This gives a value of $\sim 5 \times 10^{-13}$ s for τ. The value of τ depends mainly upon the implanting ions and dose. We believe that varying these parameters will lead to a smaller value of τ, and hence an improvement in the radiation characteristics will result.

Acknowledgements—The authors would like to thank Dr P. A. R. Ade for his assistance in carrying out the experiments and Mr D. G. Vickers for technical assistance.

REFERENCES

1. MacDonald, P. J. & D. W. Palmer, in *Lattice Defects in Semiconductors*, Inst. Phys. (U.K.) Conf. Ser. 23, p. 504 (1975).
2. Hung, C. S., *Phys. Rev.* **79**, 727 (1950).
3. Hung, C. S. & J. R. Gliessman, *Phys. Rev.* **79**, 726 (1950).
4. Mott, N. F. & W. D. Twose, *Adv. Phys.* **10**, 107 (1961).
5. Yoshihiro, K., M. Tokumoto & C. Yamanouchi, *IEEE Trans. Microwave Theory Tech.* **MTT-22** (12) December (1974).
6. El-Atawy, S. A. & P. E. Clegg, *Infrared Phys.* **16**, 409 (1976).
7. Price, P. J., *Phys. Chem. Solids* **2**, 268 (Appendix) (1957).
8. Harvey, A. F., *Microwave Engineering*, p. 40. Academic Press, London (1963).