ΑΝΑΚΟΙΝΩΣΙΣ ΜΗ ΜΕΛΟΥΣ

ΦΥΣΙΚΗ.— **Surface Recombination Velocity of InSb after electron irradiation and annealing,** *by P. C. Euthymiou and C. E. Ravanos* *. Ἀνεκοινώθη ὑπὸ τοῦ Ἀκαδημαϊκοῦ κ. Κ. Ἀλεξοπούλου.

1. Introduction

Although the result of electron and γ-ray bombardment on many properties (Hall effect, electrical conductivity, magnetoresistance) of InSb has been investigated in considerable detail [**1**, **2**, **3**, **4**, **5**, **6**], the data on the Photomagnetoelectric (PME) effect are very limited [**7**, **8**].

In the present study we investigated the influence of electron irradiation (1 MeV avarage energy) on the surface recombination velocity determined from PME measurements on p-type InSb.

Surface recombination velocity is defined by $S = J/\Delta n$ where J is the recombination current (i.e. number of recombining hole-electron pairs per unit area of surface per unit time) and Δn is the excess minority carrier density at the surface. We determined S using the expression [**9**]:

$$S = IkTB \frac{\mu_e^2}{1 + \mu_e^2 B^2} \cdot \frac{1}{i_{PME}}$$

where I is the carrier generation density (i.e. the number of hole-electron pairs produced per unit time and per unit area), k the Boltzmann constant, T the absolute temperature, B the magnetic induction, μ_e the electron mobility and i_{PME} the short circuit PME current per unit sample width. The above expression is valid when S is large enough [**9**]. This condition is fulfilled in our experiment.

The mobility μ_e is determined as follows: The above equation written in the form $B/i_{PME} = f(B^2)$ presents a straight line. The mobil-

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ity μ_e then is found from the ratio of the slope to the intercept [9]. The B and i_{PME} are measured experimentally.

The present work was further extended to the recovery of the surface recombination velocity after isochronous annealing.

2. Experimental Part

Measurements were made on specimens of p-type InSb cut from single crystal slices of two different qualities (crystal No 1 and crystals No 2 to 6). The carrier concentration p and the resistivity ϱ at 78°K were: $p = 4.8 \cdot 10^{15}\ cm^{-3}$ and $\varrho = 0.49\ \Omega \cdot cm$ for the crystal No 1 and $p = 2 \cdot 10^{14}\ cm^{-3}$ and $\varrho = 3.1\ \Omega \cdot cm$ for all the others. The samples were polished to the required size with Carborundum 220 powder and etched in dilute CP-4. They were 12 mm long (about 9 mm between the contact arms measuring the PME voltage and the DC voltage) 4 to 5 mm wide and 1.2 to 1.0 mm thick and were mounted on the end of an orthogonal copper rod of rectangular cross section in the vacuum of the cryostat. The window of the cryostat, lying at a distance of 2 cm from the specimen, was closed by a thin Mylar sheet of 25 μ thickness [4]. Irradiations and all measurements were performed at liquid nitrogen temperature. A Fe-Constantan thermocouple measured the sample temperature.

PME measurements: To measure the surface recombination velocity, we used the steady state photomagnetoelectric (PME) method. An incadescent 500 W lamp with a tungsten filament was used as the source of light. During the measurements on the crystals No 1 and No 3 the light was modulated at 80c/sec, while during the measurements on the other crystals the light was modulated at 21c/sec. A system of glass lenses ensured a uniform illumination of the sample surface. The light intensity was measured with a Model 201 Broad-Band Power Meter (Coherent Radiation Laboratories). The average wavelength of the irradiation is taken as 1.5 μ, giving a photon flux of $1.37 \cdot 10^{22}$ photons/cm^2 · sec. The quantum efficiency in this spectral region is 1.1 [7]. In this way we evaluated the carrier generation density I. Measurements were made at magnetic field induction $B = 0.1$ Weber/m^2 for crystal No 1 and $B = 0.045$ Weber/m^2 for the other crystals. The PME voltage signal equipment is composed of 1) a matching transformer, 2) a model 200 preamplifier, 3) a model 130 Synchronous Amplifier (all Brower Lab.) and 4) an Oscilloscope for the control of the coincidence of the measured signal phase to the phase of the reference signal produced in a photocell of the light chopper system.

The PME signal voltage was measured across the crystal contact arms. The DC voltage across the crystal was measured with standard potentiometer techniques using a Cambridge slide wire potentiometer. From the values of this voltage we calculated the resistivity of the crystal during illumination and application of the magnetic field. The InSb samples were irradiated by beta-particles from a $Sr^{90} - Y^{90}$ source having a nominal activity of 183 mC. The average energy of the emitted particles is about 1.0MeV and the maximum energy is 2.2MeV. The energy loss of the electrons entering the Mylar sheet window of the cryostat is negligible. The intensity of the bombarding electron beam was $5.5 \cdot 10^7$ electrons/$cm^2 \cdot$ sec. The beta source was placed under the cryostat. The annealing time chosen for each isochronal step was half an hour.

3. Effects of Irradiation

The effect of electron irradiation on the minority carrier mobility μ_e and the surface recombination velocity S is indicated in table I.

a) Minority carrier mobility. The values of μ_e are in agreement with the values of Kurnick and Zitter [**9**] for p-type InSb. Upon irradiation we find in most crystals changes that barely exceed the margin of error. However in crystals No 4 and No 5 we find a definite increase of μ_e. To our knowledge this is the first measurement of the effect of electron irradiation on minority carrier mobility. Note that all existing data [**1**, **3**, **4**, **5**] on the effect of irradiation on μ_e refer to majority carrier mobilities in the form of Hall mobilities on n-type material.

The increase of μ_e observed in our experiments may be explained as follows: The important scattering mechanisms for electrons in InSb [**10**, **11**] are polar scattering, electron-hole scattering and scattering on ionized centers. According to the existing data [**1**, **2**, **3**, **4**, **5**, **6**] on p-type InSb, irradiation with electrons or γ-rays increases the hole concentration. We do not know if the polar scattering of electrons is influenced and in what way by the increasing of hole concentration. The electron-

TABLE I

p-type InSb crystal	Sample	Irrad. time		μ_e ($m^2/V \cdot sec$)	S (m/sec) $\cdot 10^4$
$p = 4.8 \cdot 10^{15}\ cm^{-3}$ $\varrho = 0.49\ \Omega \cdot cm$ at $T = 78^0$ K	No 1	16.0 h	Before irradiation	4.95 ± 0.23	0.51 ± 0.04
			After irradiation	4.60 ± 0.23	0.47 ± 0.04
$p = 2.10^{14}\ cm^{-3}$ $\varrho = 3.1\ \Omega \cdot cm$ at $T = 78^0$ K	No 2	22.5 h	Before irradiation	7.35 ± 0.23	2.41 ± 0.18
			After irradiation	6.90 ± 0.09	2.92 ± 0.17
	No 3	27.0 h	Before irradiation	9.50 ± 0.13	8.05 ± 1.54
			After irradiation	10.00 ± 0.51	7.61 ± 1.14
	No 4	20.5 h	Before irradiation	9.45 ± 0.14	2.84 ± 0.16
			After irradiation	10.50 ± 0.12	4.43 ± 0.24
	No 5	27.0 h	Before irradiation	8.20 ± 0.30	2.33 ± 0.18
			After irradiation	9.50 ± 0.16	3.36 ± 0.37
	No 6	27.0 h	Before irradiation	8.70 ± 0.13	4.32 ± 0.25
			After irradiation	8.85 ± 0.14	4.65 ± 0.27

hole scattering is probably increased. According to the James and Lark-Horovitz model, electron bombardment generates Frenkel pairs acting as ionized donors and acceptors. The scattering mechanism on such ionized centers is affected both by the number of ionized centers and by the p-concentration. Increasing of the number of ionized centers gives a decrease of μ_e [**10**]. P-concentration can either increase or decrease μ_e depending on the range of net acceptor concentration $N_A - N_D$ if we interpret p as been proportional to $N_A - N_D$ in the measurements of Zitter et al. [**12**]. It is not possible to determine the relative importance of each effect. The observed increase of μ_e in crystals No 4 and No 5 are, hence, an indication that the factors increasing μ_e dominate. In the rest of the samples examined, the various factors cancel out, resulting in an appreciable change of μ_e .

b) Surface recombination velocity. The values of S are in agreement with the values of Hilsum et al. [**13**]. Upon irradiation we find for crystals No 1, No 3 and No 6 changes that barely exceed the margin of error. For the rest of the crystals we find a definite increase.

According to Rzhanov [**14**] S is proportional to the concentration N_t of surface recombination centers. These evidently are increasing

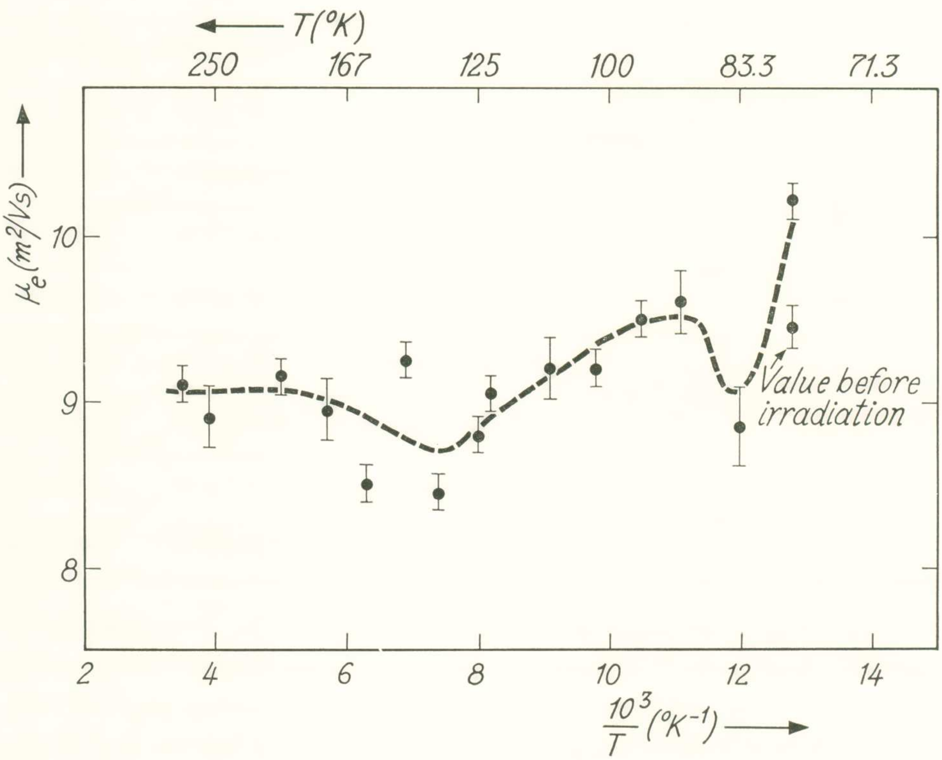

Fig. 1 : Isochronal annealing of p-type InSb crystal No 4. The curve intends to show the general trend.

upon irradiation. In the theory of Rzhanov S depends also on other parameters. It is not clear in which way these are changed upon irradiation. Such changes might influence S in a vital manner.

As mentioned above we found indeed in the present experiments a definite increase of S for 3 crystals. The fact that for the rest of the crystals the changes barely exceed the margin of error may be attributed to the contribution of the other parameters or to the recovery of the damage already at the irradiation temperature (see below).

4. Annealing

a) Minority carrier mobility. In crystals No 4 and No 5 we observe a complete recovery upon annealing already a few degrees above the irradiation temperature of 78° K (Fig. 1). The above

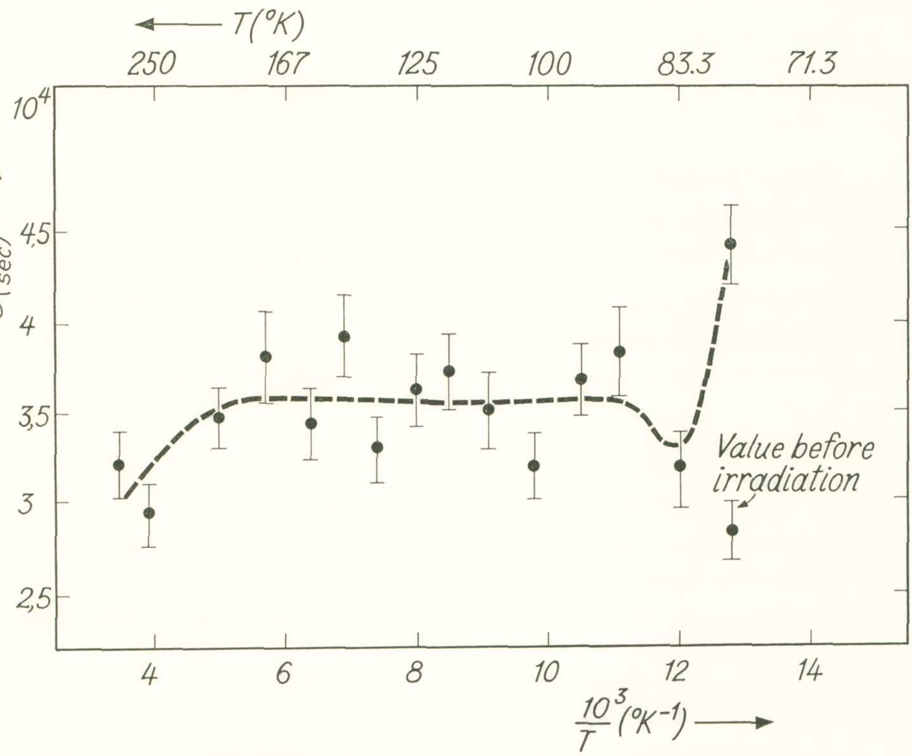

Fig. 2 : Isochronal annealing of p-type InSb crystal No 4. The curve intends to show the general trend.

mentioned recovery stage coincides with the measurements on hole concentration p [**2**, **5**, **6**] for p-type InSb.

b) Surface recombination velocity. In crystal No 4 and No 5 we observe a recovery (about 80 %) upon annealing already a few degrees above 78° K. At higher temperatures the behavior of these two crystals differ : Crystal No 4 shows no change of S upon further annealing (Fig. 2). Crystal No 5 shows a remarkable reverse annealing at about 150° K which brings S back to the value it had after irradiation. In crystal No 2 no recovery was noticed at low temperature, but above 150°K a reverse annealing seems to set in. Unfortunately the measurements are very irregular so that we cannot be sure about this statement. The fact that the annealing stage is very near the irradiation temperature suggests that a great fraction of defects was annealed during irradiation and perhaps is the reason for which we did not observe any change of μ_e or S in such crystals.

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ΠΕΡΙΛΗΨΙΣ

Τὸ φωτομαγνητοηλεκτρικὸν φαινόμενον, παρατηρηθὲν ἐπὶ μονοκρυστάλλων p-τύπου Ἀντιμονιούχου Ἰνδίου, ἐπέτρεψε τὸν ὑπολογισμὸν τῆς εὐκινησίας τῶν φορέων μειονότητος (μ_e) τοῦ κρυστάλλου καὶ περαιτέρω τῆς ταχύτητος ἐπιφανειακῆς ἐπανασυνδέσεως (S). Ἐνταῦθα μελετᾶται ἡ μεταβολὴ τῶν ἄνω μεγεθῶν κατὰ τὴν ἀκτινοβόλησιν καὶ ἐν συνεχείᾳ κατὰ ἀνοπτήσεις. Οἱ κρύσταλλοι ὑπεβάλλοντο εἰς ἀκτινοβόλησιν διὰ σωματίων β μέσης ἐνεργείας 1 MeV καὶ περαιτέρω εἰς ἰσόχρονον ἀνόπτησιν. Ἅπασαι αἱ μετρήσεις ὡς καὶ ἡ ἀκτινοβόλησις ἐγένοντο ὑπὸ θερμοκρασίαν ὑγροῦ ἀζώτου (78° K).

Εἰς δύο κρυστάλλους παρετηρήθη σαφὴς αὔξησις τῆς εὐκινησίας μ_e (11 % καὶ 16 %) μετὰ τὴν ἀκτινοβόλησιν. Εἰς τοὺς ὑπολοίπους τέσσαρας αἱ μεταβολαὶ τῆς μ_e ἦσαν ἐντὸς τῶν ὁρίων τῶν σφαλμάτων. Εἰς τρεῖς κρυστάλλους ἡ ταχύτης ἐπιφανειακῆς ἐπανασυνδέσεως παρουσίασεν αὔξησιν μετὰ τῆς ἀκτινοβολίας εἰς δὲ τοὺς ὑπολοίπους τρεῖς αἱ μεταβολαὶ ἦσαν ἐπίσης ἐντὸς τῶν ὁρίων τῶν σφαλμάτων.

Κατὰ τὴν ἰσόχρονον ἀνόπτησιν παρετηρήθη πλήρης ἐξυγίανσις τῆς εὐκινησίας ἠλεκτρονίων εἰς δύο κρυστάλλους εἰς θερμοκρασίαν κατὰ ὀλίγους βαθμοὺς μεγαλυτέραν τῶν 78° K. Ἐξυγίανσις (κατὰ 80 % περίπου) τῆς ταχύτητος ἐπιφανειακῆς ἐπανασυνδέσεως παρετηρήθη ἐπίσης εἰς ὀλίγον ὑψηλοτέραν τῶν 78° K θερμοκρασίαν εἰς ἕνα τῶν κρυστάλλων.

Τὸ γεγονὸς ὅτι εἴς τινας κρυστάλλους δὲν παρετηρήθησαν σαφεῖς μεταβολαὶ τῶν μ_e καὶ S ἀποδίδεται πιθανῶς εἰς τὴν ὕπαρξιν βαθμίδος ἀνοπτήσεως πολὺ πλησίον τῆς θερμοκρασίας ὑπὸ τὴν ὁποίαν ἐγένετο ἡ ἀκτινοβόλησις.

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Ὁ Ἀκαδημαϊκὸς κ. **Κ. Ἀλεξόπουλος** κατὰ τὴν ἀνακοίνωσιν τῆς ἀνωτέρω ἐργασίας εἶπε τὰ κάτωθι:

Ἔχω τὴν τιμὴν νὰ παρουσιάσω ἐνώπιον τῆς Ἀκαδημίας Ἀθηνῶν ἐργασίαν τῆς δίδος Παρασκευῆς Εὐθυμίου καὶ τοῦ κ. Χρήστου Ραβανοῦ ὑπὸ τὸν τίτλον «Ταχύτης ἐπιφανειακῆς ἐπανασυνδέσεως τοῦ Ἀντιμονιούχου Ἰνδίου καὶ μεταβολαὶ αὐτῆς λόγῳ ἀκτινοβολήσεως καὶ ἀνοπτήσεως».

Τὸ θέμα ἀναφέρεται εἰς τὴν μελέτην τῶν ἡμιαγωγῶν, κατηγορίας ὑλικῶν τῶν ὁποίων ἡ κατανάλωσις γενικεύεται ἀπὸ ἔτους εἰς ἔτος. Ὡς παράδειγμα ἀναφέρω τὸ γερμάνιον καὶ τὸ πυρίτιον, τὰ ὁποῖα χρησιμοποιοῦνται εἰς τὰς συγχρόνους ἠλεκτρονικὰς διατάξεις ἀντικαταστήσαντα σχεδὸν πλήρως τὰς ἠλεκτρονικὰς λυχνίας. Τελευταίως ἐπεξετάθη ἡ χρῆσις καὶ εἰς ἄλλους ἡμιαγωγούς, εἷς τῶν ὁποίων εἶναι καὶ τὸ Ἀντιμονιοῦχον Ἴνδιον.

Ἐν ἀντιθέσει πρὸς τὰ μέταλλα, εἰς τοὺς ἡμιαγωγοὺς ἡ ἠλεκτρικὴ ἀγωγιμότης ὀφείλεται εἰς κίνησιν φορτισμένων σωματίων δύο εἰδῶν. Οἱ φορεῖς οὗτοι τοῦ ἠλεκτρισμοῦ παράγονται εἴτε αὐτομάτως λόγῳ θερμικῆς κινήσεως εἴτε δι' ἀκτινοβολήσεως διὰ φωτός. Οἱ φορεῖς παραγόμενοι κατὰ ζεύγη δὲν ζοῦν ἐπὶ μακρὸν ἀλλὰ ἀλληλοεξουδετεροῦνται, φαινόμενον ἀποτελοῦν τὴν ἐπανασύνδεσιν. Ἰδιαιτέρως ταχεῖα εἶναι ἡ ἐπανασύνδεσις ἐπὶ τῆς ἐξωτερικῆς ἐπιφανείας.

Εἰς τὴν παροῦσαν ἐργασίαν ἐπενοήθη ὑπὸ τῆς δίδος Εὐθυμίου, ἐντεταλμένης Ὑφηγητρίας τοῦ Πανεπιστημίου Ἀθηνῶν, καὶ τοῦ κ. Ραβανοῦ, διδάκτορος τῶν Φυσικῶν Ἐπιστημῶν, μέθοδος μετρήσεως τῆς ἐπανασυνδέσεως. Ἡ μέθοδος προέκυψεν ἀπὸ θεωρίαν προταθεῖσαν πρὸ δεκαπέντε ἐτῶν ὑπὸ δύο Ρώσων ἐρευνητῶν, τῆς ὁποίας ὅμως ὁ ἔλεγχος οὐδέποτε εἶχεν ἐπιχειρηθῆ.

Ἡ μέθοδος στηρίζεται ἐπὶ τῆς τεχνητῆς μεταβολῆς τῆς ταχύτητος ἐπανασυνδέσεως, προκληθείσης ἐκ βομβαρδισμοῦ τῆς ἐπιφανείας τοῦ ἡμιαγωγοῦ διὰ πυρηνικῶν σωματίων. Πρὸς τοῦτο ἀπῃτήθη ἐγκατάστασις χαμηλῶν θερμοκρασιῶν κατασκευασθεῖσα ὑπὸ τῶν ἰδίων. Μερικὰ ἐκ τῶν ἠλεκτρικῶν ὀργάνων ἠγοράσθησαν δι' οἰκονομικῆς ἐνισχύσεως τοῦ Βασιλικοῦ Ἱδρύματος Ἐρευνῶν καὶ τοῦ εἰδικοῦ λογαριασμοῦ ἐνισχύσεως ἐρευνῶν τοῦ Πανεπιστημίου Ἀθηνῶν.

Τὰ ἀποτελέσματα εἶναι πολὺ ἐνθαρρυντικά, θὰ ἀποτελέσουν δὲ ἀφετηρίαν δι' ἄλλα πειράματα.