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Type conversion in electron-irradiated GaAs^{a)}

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The unambiguous type conversion of GaAs by electron irradiation is reported here for the first time. Several high-quality *n*-type vapor-phase epitaxial layers ($\rho \approx 3 \Omega \text{ cm}$ and $\mu \approx 7000 \text{ cm}^2/\text{V sec}$ at 300 K) were converted by 1-MeV electrons to high-quality *p*-type layers ($\rho \approx 30 \Omega \text{ cm}$ and $\mu \approx 400 \text{ cm}^2/\text{V sec}$). Temperature-dependent Hall-effect data show energy levels at 0.5, 0.3, and about 0.1 eV above the valence band. Evidence is presented to indicate that the failure of some of our samples (and, perhaps, other samples reported in the literature) to convert to *low-resistivity p* type is due to a rather high concentration of as-grown deep levels which pin the Fermi level near midgap.

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In spite of the rather extensive literature on electron irradiation in GaAs, the only report of type conversion, to our knowledge, has been given by Dresner.¹ His data, however, were somewhat anomalous in that the measured hole mobility of the converted crystal was only $47 \text{ cm}^2/\text{V sec}$, much too low a value considering the expected ionized defect concentrations. He interpreted his results in terms of an inhomogeneous distribution of radiation-induced defects. In contrast, the majority of the crystals that we have investigated show electrical properties after conversion indicative of high-quality crystals. Some of our crystals fail to convert to *low-resistivity p* type, but photoluminescence spectra on these crystals show deep O and Cr levels, which probably effectively pin the Fermi level near midgap.

All electrical measurements were carried out using a standard five-contact Hall-bar configuration² with indium contacts. Samples were cleaved from undoped vapor-phase epitaxial GaAs layers, 10–20 μ thick, on Cr-doped GaAs substrates. Free-carrier concentrations were $1.9 \times 10^{14} < n < 3.6 \times 10^{14} \text{ cm}^{-3}$. Samples were irradiated at 300 K with 1-MeV electrons.

Both the free-carrier concentration and the mobility were measured as a function of fluence. The results are given

in Table I. Sample HP-C-7-4-7 has the expected mobility dependence on fluence until a sharp decrease occurs just before type conversion (See Fig. 1). Note that sample HP-C-7-4-9 has a broad decrease in mobility which is similar to the results of Dresner. As will be discussed later, this broad decrease is probably due to an effect of inhomogeneity.

The mobility in type-converted samples was studied as a function of temperature. Figure 2 shows the results for HP-C-7-4-4 after fluences of 1×10^{15} and $4 \times 10^{15} \text{ e/cm}^2$. The temperature dependence of the mobility is in good agreement with previously published data on *p*-type GaAs.³ The shift to lower mobility at the heavier dose is larger than that which can be accounted for by the additional ionized-impurity scattering. A portion of the shift is probably due to the fact that the sample region beneath the indium contacts is partially shielded from the irradiation. This shielding may give rise to poorly defined contact areas (*p-n* junctions in extreme cases) which can change with fluence. Barrier-tunneling effects may also be important.

The free-carrier concentration as a function of inverse temperature is shown in Fig. 3. At a fluence of $1 \times 10^{15} \text{ e/cm}^2$, there is not a linear region sufficiently long to make an accurate determination of the energy level, but the data appear to

TABLE I. Free-carrier concentration and mobility as a function of fluence (1-MeV electrons at 300 K).

HP-C-7-4-7				HP-C-7-4-9			
Φ (10^{14} e/cm^2)	n (10^{14} cm^{-3})	p (10^{14} cm^{-3})	μ ($\text{cm}^2/\text{V sec}$)	Φ (10^{14} e/cm^2)	n (10^{14} cm^{-3})	p (10^{14} cm^{-3})	μ ($\text{cm}^2/\text{V sec}$)
0.0	3.61	...	7140	0.0	1.87	...	6570
1.5	2.33	...	7120	0.5	1.65	...	6320
3.0	1.27	...	7150	1.0	1.48	...	6010
4.0	0.51	...	7080	2.0	1.34	...	4850
6.0	0.18	...	5550	4.0	5.31	...	636
8.0	0.30	...	1410	6.0	...	2.64	410
10.0	...	0.86	349				
12.0	...	0.72	329				
14.0	...	0.61	299				

^{a)}Work performed at the Avionics Laboratory, Wright Patterson AFB under contract F33615-76-C-1207.

FIG. 1. Mobility versus fluence. The fluence is normalized to the initial carrier concentration n_0 . The solid portion of the smooth curves indicates n -type conductivity, while the dashed portion indicates p type.

approach a slope corresponding to an energy of ~ 0.1 eV above the valence band. At fluences of 4×10^{15} and 1×10^{16} e/cm², energy levels of 0.3 and 0.5 eV, respectively, are clearly obtained. An 0.1-eV level has been reported in irradiated p -type GaAs,^{4,5} and levels at 0.1, 0.3, and 0.5 eV from the

FIG. 2. Mobility versus temperature at two fluence values for sample HP-C-7-4-4.

FIG. 3. Free-carrier concentration versus inverse temperature. Energy levels of ~ 0.1 , 0.3, and 0.5 eV from the valence band are found at fluences of 1×10^{15} , 4×10^{15} , and 10×10^{15} e/cm², respectively. Fluences of 1×10^{15} and 4×10^{15} e/cm² are for sample HP-C-7-4-4, while the 10×10^{15} e/cm² fluence is for sample HP-C-7-4-7.

valence band have been reported in deep-level transient spectroscopy (DLTS) studies of irradiated n -type samples.⁶

The results of a 30-min isochronal annealing study of sample HP-C-7-4-4 are given in Table II. The sample reverts to n type at 250 °C. Before reverting, the sample shows a p -type recovery stage, in good agreement with reports of annealing in irradiated p -type GaAs.⁷

Dresner attributed the anomalous mobility and the type conversion to inhomogeneous effects resulting from the radiation-induced migration of deep donors. We feel that the more detailed study of type conversion presented here yields a simpler explanation. We assume that the irradiation introduces a uniform distribution of donors and acceptors. The dependence of the mobility on fluence is then an indication of the degree of spatial fluctuation in compensation, i.e., the homogeneity of the sample. In our model, the fluctuation occurs during crystal growth and is not significantly affected

TABLE II. 30-min isochronal anneals of sample HP-C-7-4-4. Preirradiation $n = 2.11 \times 10^{14}$ cm⁻³ and preanneal $p = 2.18 \times 10^{13}$ cm⁻³.

T (°C)	n (10^{13} cm ⁻³)	p (10^{13} cm ⁻³)
100	...	2.10
125	...	2.19
150	...	2.45
175	...	2.78
200	...	2.95
225	...	3.35
250	3.53	...
275	11.20	...
300	15.60	...

by the irradiation. Samples HP-C-7-4-7 and HP-C-7-4-9 provide an example of a case in which slight variations in the homogeneity are accentuated during the type-conversion transition. Both samples are macroscopically homogeneous (as determined from transport properties) before *and* after type conversion. However, the sharper mobility transition of HP-C-7-4-7 indicates that this sample is slightly more homogeneous than HP-C-7-4-9 (see Fig. 1). The *apparent* increase in n just before type conversion, seen in both samples (see Table I), is also probably due to the inhomogeneity of the sample during the transition from n to p type; i.e., the negative Hall coefficient may be artificially low due to positive contributions from the p -type portions of the sample.

The three defect levels found in this work agree very well with the data in the literature. The 0.1-eV level has been reported in conductivity studies of irradiated p -type GaAs. Both the 0.3- and the 0.5-eV levels have been seen in DLTS studies of irradiated n -type samples, but our work is the first observation of either level from electrical measurements

It is perhaps useful to discuss the near absence of reports of type conversion in irradiated GaAs. We feel that it is significant that conversion to *low-resistivity* p type is seen only in samples which show neither O nor Cr photoluminescence lines (0.66 and 0.8 eV, respectively). Whether the absence of both centers is necessary or just sufficient has not yet been determined. The presence of high concentrations of these deep centers will tend to pin the Fermi level near mid-gap. Consequently, a correspondingly high concentration of shallow acceptors must be introduced to overcome the pin-

ning effects of the deep levels. Even in high-purity VPE GaAs layers, O and Cr are often observed in photoluminescence; therefore, many available samples will not readily type convert to low-resistivity p type.

In summary, we have shown that electron-induced type conversion provides a new method of obtaining high-purity good-quality p -type samples (we have obtained room-temperature mobilities as high as $410 \text{ cm}^2/\text{V sec}$). The relatively low-temperature annealing characteristics of these p -type samples limits their technological applications to operating temperatures less than 200°C . However, the possibility of type conversion greatly enhances the usefulness of electrical measurements in the study of point defects in GaAs, in that the Fermi level can be varied throughout the gap in the same sample.

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