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Characterization of defects in gallium arsenide

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Abstract. It is well-known that the properties of semiconductor materials including gallium arsenide are controlled by defects and impurities. The characterization of these defects is important not only for better understanding of the solid state phenomena but also for improved reliability and performance of electronic devices. We have been investigating the defects in gallium arsenide for several years using deep level transient spectroscopy, photoconductivity, transient photoconductivity, photoluminescence etc. Results drawn from our recent studies are presented here to illustrate some of the problems concerning transition metal impurities, process-induced defects, occurrence of intracentre transitions and metastability of deep levels in gallium arsenide.

Keywords. Gallium arsenide; deep level transient spectroscopy; semi-insulating gallium arsenide; photoconductivity; photo luminescence.

1. Introduction

Gallium arsenide has several intrinsic defects (Kaufmann and Schneider 1982; Milnes 1984). In addition, transition metal impurities (Clerjaud 1985) are often inadvertent contaminants incorporated during device processing. Deep level defects in gallium arsenide have several interesting features including metastable states. The investigations reported here reveal some interesting properties of the deep level defects in GaAs.

The techniques used for these investigations are fairly standard in any semiconductor laboratory. These include deep level transient spectroscopy (DLTS), optical transient current spectroscopy (OTCS), photoconductivity (PC), photoluminescence (PL) etc. No introduction to these techniques is given here and can be found in the literature (Bourgoin and Lannoo 1981).

2. Deep levels due to transition metals

As mentioned above, transition-metal impurities are often unintentional contaminants in semiconductor materials. Chief among these impurities are copper and iron. Nickel is also suspected to be present in GaAs. Nickel-related energy levels in the band gap of GaAs have been studied by several authors (Kumar and Ledebo 1981, and references therein). However, serious discrepancies in the published data can be noticed. We have studied the properties of nickel-related levels by introducing nickel either by diffusion or during liquid phase epitaxy (LPE) growth. When Ni is introduced during LPE, no related level is detected by DLTS. When diffused, it gives rise to a level which has properties identical to those of copper in GaAs. The properties studied include activation energy, thermal capture cross-sections for holes and electrons, and photoionization cross-sections for holes. Hence, it has been concluded that the $E_v + 0{\cdot}4\,\mathrm{eV}$ level attributed to nickel by earlier workers is indeed related to copper in gallium arsenide.

Other transition metal impurities studied in this laboratory include Fe

(Kalyanraman and Kumar 1980) and Ag (Pandian and V Kumar 1988, unpublished data) where the results obtained are consistent with the reports in the literature.

3. Electron trap in *n*-type LPE-GaAs

Gallium arsenide grown by LPE from a Ga-rich melt, in general, does not give rise to any trap in the upper half of the bandgap. This is explained by the fact that incorporation of impurities or defects at Ga sites is less likely when grown from Ga-rich melts as in LPE. However, surprisingly, in layers grown by LPE in our laboratory we frequently observe a majority carrier electron trap. DLTS spectra of this trap have been recorded for various time-constant windows. The Arrhenius plot obtained from these measurements is shown in figure 1. The activation energy of the trap is determined to be 0·607 eV and the capture cross-section $\sigma_n = 1{\cdot}45 \times 10^{-14}\,\mathrm{cm}^2$. The concentration of this trap, whose physico-chemical origin is as yet unknown, is estimated to be $4{\cdot}6 \times 10^{14}\,\mathrm{cm}^{-3}$. An optical DLTS spectrum of this material is shown in figure 2. Here, in addition to the above mentioned electron trap we also observe a hole trap with an activation energy of 0·52 eV. The trap signature indicates that it could be due to iron contamination.

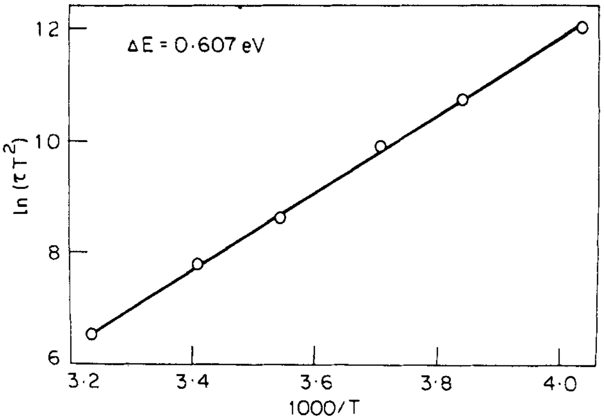

Figure 1. Arrhenius plot for the electron trap in LPE-grown *n*-type GaAs.

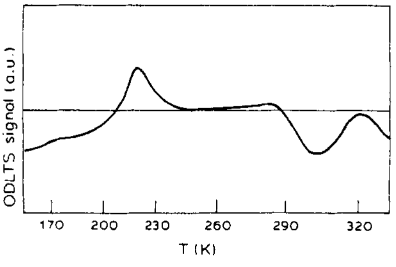

Figure 2. Typical ODLTS spectrum of LPE-grown *n*-GaAs showing a low temperature minority carrier trap and a high temperature majority carrier trap for a rate window of 70·61 s^{-1}.

4. Chromium-doped semi-insulating GaAs

Semi-insulating gallium arsenide has wide technological applications as substrate material for high speed switching devices and integrated circuits. Optical transient current spectroscopy (Martin and Bois 1978) is a convenient method of characterizing deep levels in such high resistivity materials. There have been interpretational problems (Deveaud and Toulose 1980; Kremer *et al* 1987) in applying this technique to Cr-doped SI-GaAs. We observe two peaks (Mohapatra *et al* 1985), one positive and the other negative, in the OTCS spectra of this material in the temperature range 300–450 K. The positive peak is due to a trap at $E_c - 0{\cdot}47$ eV. The anomalous negative peak at $E_v + 0{\cdot}88$ eV is explained by the peculiar property of the trap being able to catch electrons from the conduction band even though it is a more efficient hole emitter. This peak is attributed to the chromium acceptor level.

The photoconductivity spectrum of the Cr-doped SI-GaAs, as shown in figure 3, has among other features two sharp peaks at 0·83 and 0·87 eV. The sharpness of these peaks clearly indicates that these are due to transitions between discrete levels. Earlier reports (Lin and Bube 1976; Look 1978) have mentioned only a broad peak and attributed it to an intracentre transition. This is the first report of the second peak at this energy though we are unable to assign it at this time. The PL spectrum shown in figure 4 has only one sharp line at 0·839 eV which has been attributed to an intracentre transition of Cr^{3+} ion.

5. Photo-conductivity of LEC-grown semi-insulating GaAs

The semi-insulating nature of LEC-grown undoped GaAs has been attributed to a trap commonly known as EL2. This centre has many interesting and unusual

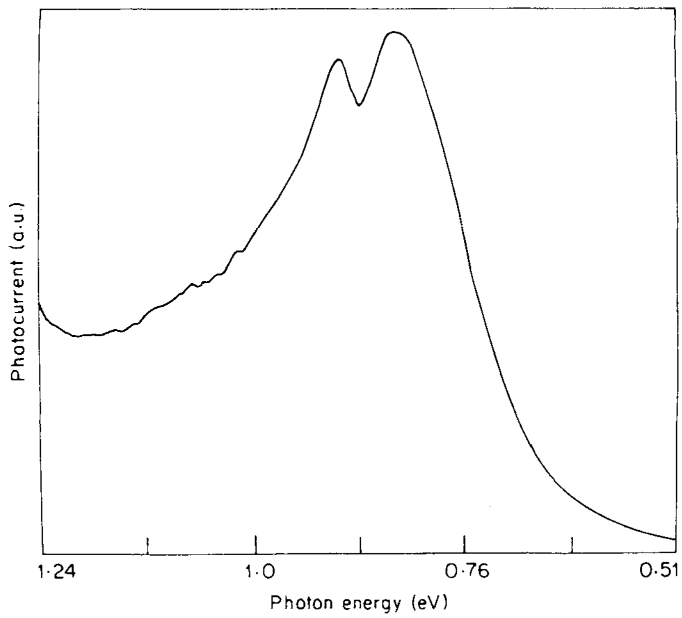

Figure 3. Photoconductivity spectrum of Cr-doped semi-insulating GaAs at room temperature showing evidence of two intracentre transitions.

properties, including its ability to be converted to an optically induced metastable state at low temperatures. The rate of conversion from the metastable to the normal state is thermally activated. We have recently proposed a new and reliable method (Mohapatra and Kumar 1988) of measuring this activation energy in semi-insulating GaAs. The technique, best described as the thermally stimulated photocurrent (TSPC) method, consists of monitoring the temperature, at which a step in photocurrent occurs due to the process of conversion, as a function of heating rates. A typical set of TSPC plots showing the shift of the step with heating rates is given in figure 5. Analysis, analogous to the thermally stimulated capacitance (TSCAP) method (Sah *et al* 1972), is carried out to obtain the activation energy (0·26 eV) and the attempt-to-convert frequency ($2{\cdot}5 \times 10^8\ \mathrm{s}^{-1}$) for the process of conversion from the metastable to the stable state.

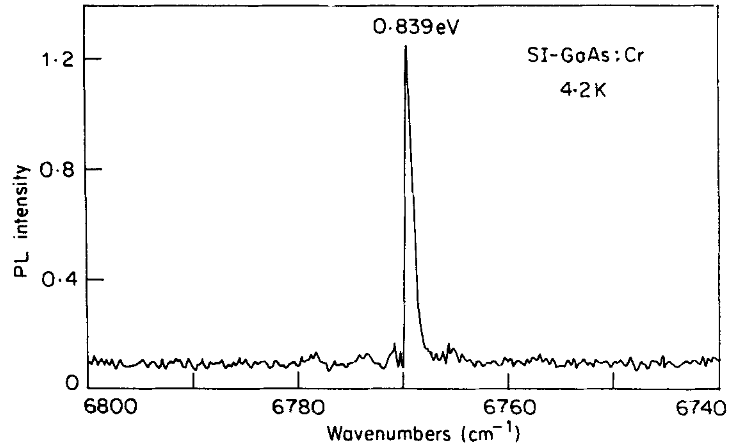

Figure 4. Photoluminescence spectrum of Cr-doped semi-insulating GaAs at room temperature. The source of excitation is an argon ion laser operating at 514·5 nm.

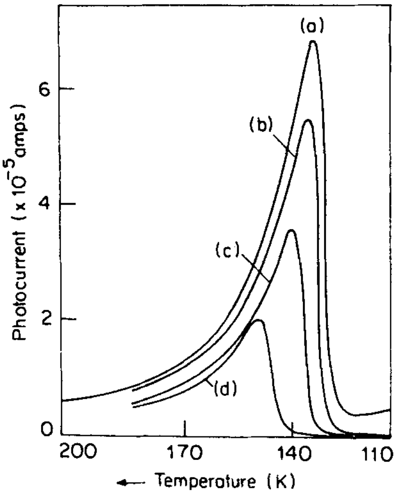

Figure 5. Typical TSPC plots for undoped semi-insulating GaAs showing temperature shift of the step for various heating rates (in K/s): (a) 0·158 (b) 0·22 (c) 0·487 (d) 2·266.

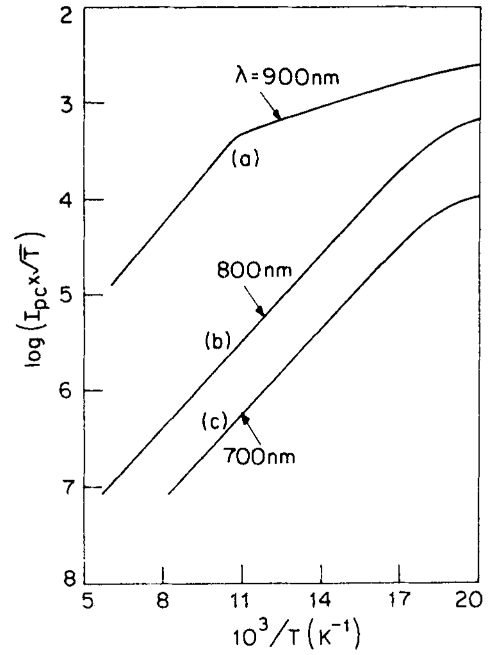

Figure 6. Photocurrent (in log scale) vs $1000/T$ plots for undoped semi-insulating GaAs for three different wavelengths of illumination. The slope of the linear portions yield an energy of 0·06 eV.

The photocurrent in this material increases exponentially with decreasing temperature when EL2 is in its normal state as shown in figure 6. Since transfer of EL2 to metastable state EL2* also reduces the photocurrent, it is inferred that EL2 controls both extrinsic and intrinsic photocurrent. The observed temperature dependence is attributed to the temperature dependence of the hole capture cross-section of EL2 which has the activation energy of 60 meV (Mohapatra and Kumar 1989).

6. Concluding remarks

In summary, we have discussed several distinctive features of deep level characterization in gallium arsenide through recent results of our studies. Several other defects in GaAs have been investigated in this laboratory including the well-known DX centre in GaAlAs (Subramanian *et al* 1986). However, many of the defects including EL2 and DX remain to be fully understood in spite of wide-ranging studies throughout the world because of their technological importance.

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