Transport Properties of Heavily Doped $Al_{0.3}Ga_{0.7}As$ Semiconducting Alloys

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The transport properties of doped and heavily doped $Al_{0.3}Ga_{0.7}As$ alloys is studied as a function of temperature and light doses. All the sainples were beyond the Mott transition limit and some of them beyond the self compensation limit. We have investigated the free carrier concentration measured by Hall effect. We observed different activation energies for the DX center as a function of impurity concentration. Excitation of the samples using an infra-red source was also provided in order to pursue a better insight in the DX center population behaviour. We correlated the incremental free electron photo persistent population with the activation energies obtained from the temperature dependence of the measured Hall concentration. We concluded that large impurity concentrations can yield perturbations in the lattice potential that may alter the barriers for capture and emission of electrons by and from DX centers respectively.

I. Introduction

The study of transport properties of AlGaAs alloys has been receiving a fair amount of attention in the past years due to the PPC (persistent photo-conductivity) phenomena associated with the so called DX center. This effect occurs for example in silicon doped AlGaAs sainples with an aluminum content greater than 22%. When exposed to light PPC was characterized by an irreversible "reaction" valid for temperatures lower than aproximately 100 K, namely

$$DX^- + D^+ \rightarrow 2e^- + 2D^+ \qquad (1)$$

It is nowadays well established that the DS center is formed by a substitutional donor atom that under suitable cooling conditions moves outside its original site to an unrelaxed position, causing a local deformation in the lattice potential. In this situation the donor's ioii gets two electroiis in oider to minimize its energy, which has been altered due to its new position in the lattice.

The DX concentration increases with the nominal iinpurity concentration as demonstrated by previous works[1]. As a matter of fact, as the impurity concentration is increased well beyond the Mott limit, the relative DS concentration begins to drop, indicating that the system cannot minimize its energy by producing DX centers. This fact can be understood as we take into account the increase in the concentration of other defects[2] that disturb the lattice potential in a way that it is iiot possible to stabilize the donor ions with two electrons.

Another effect induced by high doping levels is the broadening of the shallow donor level yielding a impurity band, with peculiar transport properties[3]. The role of this impurity band levels in the capture and emission processes must also be taken into account in order to explain the observed smaller activation energies and the different DX concentration.

In this work we studied the free electron population dependence with temperature and light doses. We have carried out the Hall measurements in AlGaAs samples with an aluminum content percentage of 30% and silicon as the n-type dopant. The data analysis did not take into account the conduction band density of states dependence with the temperature. We obtained the slopes of Arrhenius plots which are related to the activatioii energies. We discuss also the relative increment in the free carrier concentration and its relation with the energies taken from the Arrhenius plots.

Table I - Impurity nominal concentration and other parameters obtained from the measured Hall concentration as a function of temperature

Sample	1	2	3	4
Silicon Nominal Concentration(cm^{-3})	4×10^{17}	3×10^{18}	9×10^{18}	3×10^{19}
Arrhenius Slope (meV)	81	15	19	31
$\Delta n(1 \times 10^{18} cm^{-3})$	0.5	2	2.35	1.58
$n_{77K}(cm^{-3})$	9×10^{14}	1×10^{18}	7.5×10^{17}	2.2×10^{17}

II. Experimental aspects

The four samples (labeled 1 to 4 in asceiiding order of Si concentration) were grown in semi-insulating GaAs (100) substrate in a RIBER 2300 R&D MBE (molecular beam epitaxy) apparatus. The aluminum was content fixed at 30 percent and the substrate temperature at 620°C. The silicoii nominal concentration ranged from $4 \times 10^{17} cm^{-3}$ to $3 \times 10^{19} cm^{-3}$, as obtained from previous machine calibration procedures. A 3000Å thick unintentionally doped GaAs buffer layer was followed by a. 5000Å thick $Al_{0.3}Ga_{0.7}As$ also unintentionally doped layer. After that, a silicoii doped active layer 2.8μm thick was grown and at last a silicoii doped GaAs cap layer with an approximate thickness of 60Å. Table 1 shows silicon nominal concentration for each sample.

Hall measurements were carried out in a liquid nitrogen/helium cooletl cryostat with standard Hall bridges photolithografic fabricated with alloyed Au-GeNi ohmic contacts. The infra-red light source was a LED with a radiation emission centered at 1.32 eV. Tlie measurement procedure included a.two step thermal cycle; a cool down ramp with a constant rate of 1°C/min and a heat ramp with a constant rate also fixed in 1°C/min. The cryostat was appropriately shielded for any radiation. In all samples we have pursued a.saturation condition at low temperature, providing tlie maximum light intensity available with the LED. The experiment was carried out in a fully automated system controlled by a PC computer.

III. Results and discussion

Basically two models exist for the charge state of DX. One supposes that in the most favored conditions the silicon atom ions stabilize hy taking two electrons and becoming negatively charged. The other supposes that tlie silicon atoms take just one electron and hecome neutral. The former is known as negative C model, characterized by an negative effective correlation energy, while tlie later positive U model. It is difficult to make a. distinction between the two models using only temperature dependent Hall measurements[4]. In this way, we do not try to distinguish the two models. We discuss our data assuming that we can rcpresent tlie Hall concentration dependence with the temperature by an Arrherius law, namely

$$n \propto \exp(-E_{DX}/kT) \qquad (2)$$

In fact this is a. crude approximation, since some of the samples are beyond the degenerate lirnit and also because the temperature dependence of the effective density of states of the conduction band was not taken into account. Even though, we helieve that tlie Arrhenius slopes are representative figures to give reasonable description of the studied system.

Figure 1 cxhibits the observed temperature dependence of the Hall concentration in tlie dark. We can clearly observe that tlie self compensation limit was achieved and for samples 3 and 4 the nicasured carrier concentration is smaller than in sample 2, although tlie silicoii concentration is higher. All tlie studied samples are beyond tlie Mott limit.

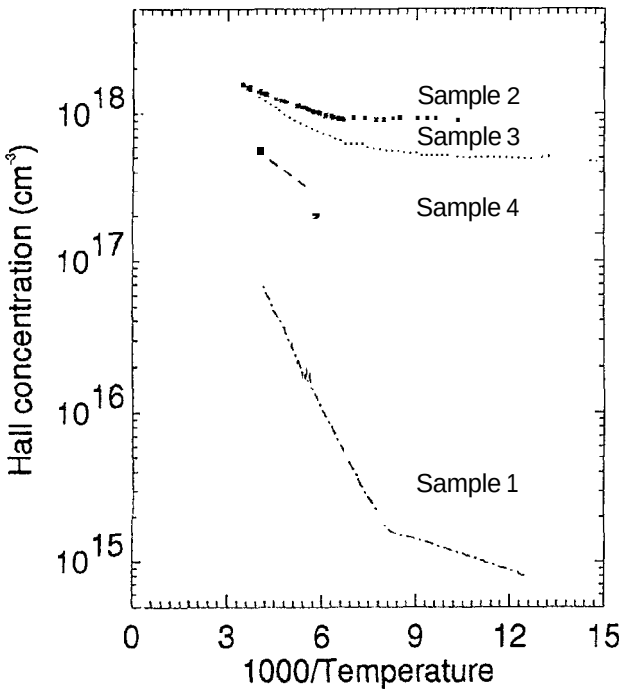

Figure 1: Temperature dependence of tlie measured Hall concentration.

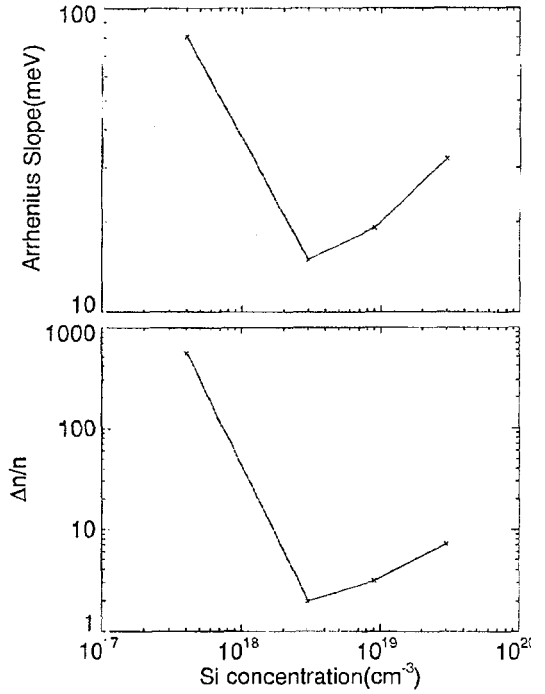

Figure 2: Upper plot - Dependence of tlie Arrhenius slopes obtained from the temperature dependence of tlie Hall concentration with tlie silicon concentration; Lower plot - Dependence of the PPC effect, here expressed as $\Delta n/n$ measured at 77K, with tlie silicon concentration.

The obtained activation energies froin the high temperature portion of the curves shown in Fig. 1 are summarized in Table 1 and are depicted in Fig. 2. Also in Fig. 2 we show the increment ratio, An, of the values obtained at 77 K under illumination (saturation condition) and in darkness. This ration gives information about the DX concentration, which is related to PPC effect. We observe that the PPC effect, at least qualitatively, follows the activation energy dependence on tlie silicon concentration. To explain such behaviour we must in the first place take into account perturbations in the lattice due to the increasing concentration of defects such as Si_{As}, Si_{As}-Si_{Gn} and all others that may arise in high doping conditions[2,5-7]. We must also address the importance of screening effects that are particularly important in the metallic regime. The high doping limit can be estimated from the relation

$$Na^3 = 1\ , \qquad (3)$$

where A' is tlie impurity concentration and a is the effective Bohr radius. For $Al_{0.3}Ga_{0.7}As$ we have N $\simeq$ 2.0 x 10^{18} cm^{-3}. It is interesting to note that the concentration at which the PPC effect and the DX activation energy have a minimum is close to this limit. We can identify then two distinct competing mechanisms tliat are responsible for tlie PPC effect and DX activation energy behaviour beyond the high doping limit, tlie screening decreasing and the self compensation increasing both quantities. We can also expect the same behaviour for the screening length due to its dependente with the free electron concentration (for the free electron concentration at 77K dependence with N_{Si}, see Table 1). We believe that this corroborates our picture of tlie studied system.

IV. Conclusion

We studied $Al_{0.3}Ga_{0.7}As$ alloys far beyond the Mott limit and some of then beyond the self compensation limit. We observed that the concentration of new defects yields a competition between them and screening effects to favoring and inhibiting DX centers formation. Beginning with the least doped sainple, we observe a decrease followed by an increase of the Arrhenius slopes

and also the increment in the Hall concentration from dark to strongly exposition to IR light at low temperatures.

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