Photoinduced Conductivity in n-type $Al_xGa_{1-x}As$ at Low Temperature

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We have measured the photoconductivity spectrum for Si-doped $Al_xGa_{1-x}As$ samples at 10 K. Tlie behavior is quite different whether the material lias a direct or indirect bandgap. Photoconductivity of $Al_xGa_{1-x}As$ with a direct bandgap is influenced by persistent photoconductivity (PPC) whereas indirect bandgap material presents no PPC but a photoconductivity minimum at 565 nm. Transient decay of persistent photoconductivity observed for indirect bandgap material in tlie range 80-100 K, can not be explained by a single channel conduction model and our proposed model predicts tlie participation of an L valley effective mass state in tlie DX center trapping kinetics. For lower temperature, both L and X valley effective mass states are responsible for the observed behavior, depending on the temperature range

I. Introduction

It is well known that n-type $Al_xGa_{1-x}As$ presents a localizcd state called a DX center. which appears to be related to tlie substitutional donor[1], although this interpretation is still a. matter of controversy[2]. In this crise, tlie DX center is a state of the impurity donor, which can cxist in either of two distinct lattice configurations, eacli of which has its own spectrum of bound electronic states. According to tlie most accepted model[3] , tlie DX center is tlie donor itself which traps two electrons and becomes located at an intcrstitial position. The defect exhibits negative effective correlation energy (negative U) with strong electron phonon coupling. Tlie distorted configuration is stabilized by capture of two electrons. The DS center has a thermal y activated capture cross section and it is responsible for tlie transport properties below $\simeq$ 1150 K. Such a. capture cross section leads to a property known as persistent photoconductivity (PPC), which masks the photoconductivity spectrum at liquid nitrogen temperature, because when excited to the conduction band, electrons will not return to the non-conductive state, trapped at DX centers, very quickly. It would take a few hundred seconds or even hours, depending on the magnitude of the capture barrier. Thus, any other transition will not be seen.

Particularly in the case of indirect bandgap $Al_xGa_{1-x}As$, the lowest conduction band minimum is the X valley. The hydrogenic state associated with tlie X valley is also deep and thus, it is able to capture photogenerated electrons metastably[4,5]. There is no reason to believe that there is a barrier for electron capture by this X valley effective mass state, since there is no lattice relaxation involved. Raman scattering experiments[6] on n-type GaAs under hydrostatic pressure have revealed the existence of bound phonons associated with electrons trapped at an effective-mass like level. Bound phonons are only observable if associated with neutral donors[7].

DX centers are present in $Al_xGa_{1-x}As$ alloys of any aluminum composition, but the recombination processes after illumination is quite different if the sample lias direct or indirect forbidden gap depending on the temperature range. We present results for both situations and discuss the contribution of impurity donor states.

II. Transient decay of persistent photoconductivity in indirect bandgap $Al_xGa_{1-x}As$

Since the capture cross section is thermally activated (follows Arrhenius law), the electron trapping by DX centers can be measured at different temperatures. Transient decay of persistent photoconductivity (TDPPC) is observed in experiments where the decay of conductance is measured for several temperatures in tlie range SO-100 Ií and has been described elsewhere[8]. Experimental data are numerically simulated and then, the capture cross sectioii and tlie trapping mechanisms can be evaluated. TDPPÇ data in direct bandgap AlGaAs lias been simulated[8,9] using simple relations to moclel each term of tlie conductivity equation:

$$\sigma(t) = en(t)\mu(t) \qquad (1)$$

where e is tlie electronic charge, n is tlie time dependent free electron concentration and μ is tlic mobility, whicli is also time dependent. The Brooks-Herring mobility equation is used, since in tlie employed range of temperature and free carrier concentration, deviations due to the field generated by colliding electrons, which deforms the screening cloud[9,10], are iiot significant. The agreement with experimental data is very good when we use the capture kinetics based on Chadi and Chang's model[3] plus a photoinduced shallower donor.

Por indirect bandgap $Al_xGa_{1-x}As$, where $x \simeq 0.5$ (growth calibration), doped with approximately 5×10^{17} Si atoms/cm^3, tlie obtained TDPPC experimental curves have similar shapes to those obtained for direct bandgap material, although the magnitude of conductance is never comparable to them. Such an order of magnitude assures tliat there is no 2DEG conduction since tlie conductance in the sample is much lower than the conductance at room temperature, which is not shown in the Fig. 2, and TDPPC data results from DX center capture, decreasing the condiiction band population. All the attempts to simulate the experimental data using the siinple models proposed for direct bandgap $Al_xGa_{1-x}As$ give poor results. In this case the mobility is obtained assuming that all the electrons are excited to the X valley, which has the lowest conduction band minimum at this Al composition. It appears physically non-realistic tliat there could be electrons in other valleys at 80 K and $x \simeq 0.5$ [11]. However, in the TDPPC experiment the sample is illuminated with a strong below bandgap light, leading to a. clearly non-equilibrium situation. Thus, it is possible that, besides the X valley, there will be electrons in other valleys. Our choice is assume that there are electrons also in the L valley, whose minimum is close to the X valley minimum. It has been argued by several researchers[12-14] that there is an intermediate state which can be a metastable neutral state of the donor impurity, associated with the donor in its substitutional site[12], or at an interstitial site (DX^0)[14]. Any attempt to fit experimental data should take into account such an intermediate state, whicli is located above the X valley minimum (the intermediate state can be pictured as tlie activated complex of the reaction : $d^+ + 2\ e^- = DX^-$). Thus it raises another possibility: if the intermediate state level is located above the X valley minimum, it is close to tlie L valley. Such a. picture allows tunneling between L valley and intermediate state. Our numerical moclel to simulate TDPPC experimental data based on this approach does not lead to satisfactory data fitting. It does not mean that there is no intermediate state in the DX center capture, however if more than one valIcy participates in tlie conductive state, to consider an intermediate state hardly improves tlie fit. Models using intermediate states to explain kinetic mechariisms must consider that transitions between deep and shallom states through an intermediate state have comparablc rates, otherwise one of these processes will dominate the recombination and only its rate will matter in the kinetics moclel.

Our second choice is based on the effective mass approach which produces delocalized effective mass states pinned to the relevant band minimum[5]. Depending on the composition, the dominant hydrogenic donor level may be Γ-like, L-like or X-like[1]. The X valley effective mass state could be an intermediate in the electron trapping. Although this state dominates the transport properties below 60 K, in the range of temperature where TDPPC experiments are carried out, it would keep the electrons only for a negligibly short time that would not modify the capture kinetics significantly. We then assume that an L valley effective mass state participates in the capture, since it is resonant with the X valley, and thus, tunneling between X valley and this L valley effective mass state is allowed as shown in Fig.1.

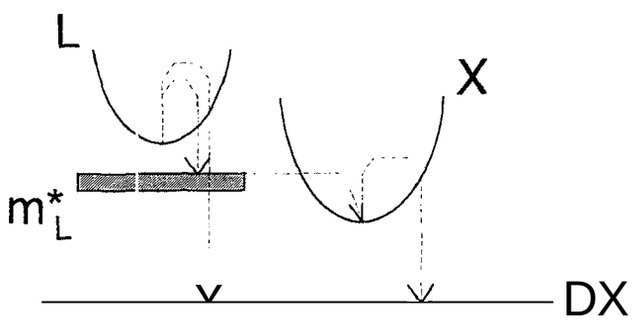

Figure 1: Model for the trapping kinetics by DX center using double channel conduction and participation of tlic L valley effective mass state.

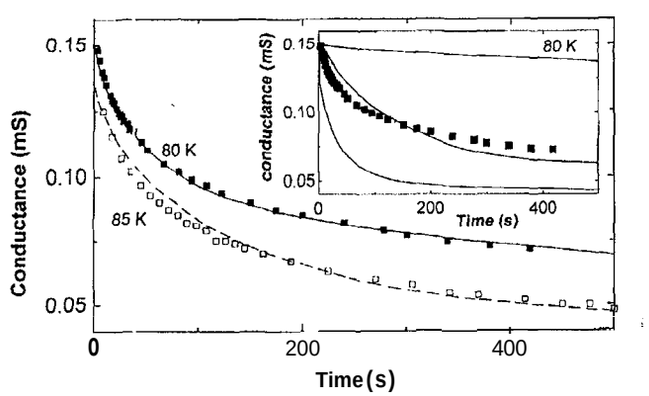

Figure 2: Fit to SDPPC experimental data using double channel conduction model. Inset - Attempt to fit data using a single channel conduction (X valley). From tlie upper to the lower curve - capture barrier = 0.24 eV, 0.22 eV, 0.20 eV respectively.

Therefore, our model assumes double channel conduction and capture by the metastable L valley effective mass state, besides the DX center, suggesting the possibility of tunneling between the L valley effective mass state and the X valley. Equations to simulate electronic population in this model are :

$$\frac{dn_L}{dt} = -FATV_{th}\sigma_{DX}\frac{n_L^2}{2} - (1-FAT)V_{th}\sigma_{MET}n_L^2 \quad (2)$$

$$\frac{dm_L}{dt} = (1-FAT)V_{th}\sigma_{MET}n_L^2 - C_{TUN}m_L \quad (3)$$

$$\frac{dn_X}{dt} = -V_{th}\sigma_{DX}\frac{n_X^2}{2} \quad (4)$$

where n_i is the electron concentration in the i valley, V_{th} is the electronic thermal velocity, σ_{DX} is the DX center capture cross section, FAT is the fraction of electrons trapped from the L valley into DX center and electrons trapped at the L valley effective mass state, m_L is the neutral L valley effective mass state concentration, σ_{MET} is the capture cross section of this state and C_{TUN} is the tunneling constant hetween the L valley effective mass state and the X valley. Since the illumination intensity is very strong, we consider that all the electrons are excited and $n_i(0)$ is an adjustable paramcter in addition to FAT and C_{TUN}. Tahle I shows the fitting parameters used in our approach.

Table I - Fit parameters for double channel conduction model.

temperature (K)	n_x (10^{17} cm^{-3})	FAT	C_{TUN}(sec^{-1})
80	2.22	0.36	$1.9\text{x}10^{-4}$
85	1.87	0.78	$9.0\text{x}10^{-5}$
90	1.74	0.80	$1.1\text{x}10^{-4}$
95	1.68	0.83	$2.0\text{x}10^{-5}$
100	1.50	0.84	$5.0\text{x}10^{-5}$
105	2.20	0.73	$1.0\text{x}10^{-6}$

The parameters values are a. good indication that our model is quite reasonable. The X valley initial concentration decreases with temperature (except for 105 K) which is expected, since the electrons will have higher thermal energy to populate higher levels (L valley). The FAT slightly increases with temperature (except for 105 K) indicating that more electrons are being directly trapped by DX centers instead of going to the L valley effective mass state. This seems seasonable since

tlie effective mass metastable trapping becomes more important as tlie temperature is reduced. The order of magnitude of C_{TUN} indicates a small tunneling rate of electrons trapped at I, valley effective mass state to the X valley. Examples of fit using this approach are shown in Fig. 2 for 80 K aiid 85 K. The inset in Fig. 2 represents attempts to fit TDPPC experimental data using electronic population only in the X valley and DX trapping directly from tlie X valley. The parameters used at 105 Ií (table I) indicates that new recombination processes may be occurring for temperatures higher than 100 Ií and probably, emission processes should be taken into account.

III. Photoconductivity influenced by substitutional donor states

The photoconductivity spectrum at 10 K for a direct bandgap $Al_xGa_{1-x}As$ sample is shown in Fig. 3. The exciting light comes from a tungsten lamp of a. Cary spectrophotometer with constant bandwidth output. The wavelength is scanned from higher to lower value, at a scanning speed of 50 nm/min. This is a. clear evidence of tlie DX center presence, since the photoconcluctivity increases when tlie wavelength is about the bandgap transition and persists in this conductive state, because there is not enough thermal energy for electrons to overcome the thermal capture barrier. The inset in fig. 3 confirms this beliavior since the sample is illuminated with a sub bandgap monochromatic light of 560 nm for 600 seconds, then the illumination is removed and tlie resistance becomes constant. Trappiiig by the A_1 state, which does not present a. barrier foi electron trapping, having a very short capture time[15] was not seen in our measurements. The estimated bandgap from the photoconductivity spectrum is about 1.96 eV, which means an aluminum composition x≃0.32, calculated considering the temperature corrections[16].

For indirect bandgap $Al_xGa_{1-x}As$, when tlie temperature is lowered below 60 K, the transport properties are dominated by the X valley effective mass state[4,5]. Conductivity as a. function of wavelength at 10 K is shown in Fig. 4. A striking result is obtained: light does not have any effcct in the conductivity, presenting tlie same value as iri the dark (the highest value in fig. 4), and remaining unchanged for the whole range of wavelengths except the region near 560 nm, where a negative photoconductivity is obtained. It suggests that excitation and recombination processes can ot be described by the same equations of the previous section, siiice there is no PPC. Vanishing of PPC can be observed in the inset of Fig. 4, where TDPPC experimental data is obtained at 50 K. After the ilumination is removed, conductance decays very quickly. Our curve starts from one second (measurement delay) and most of the signal lias already disappeared. The decay lasts a few seconds and the conductance becomes stationary. Short peaks seen in the insert indicate only iioise, since the magnitude of measured conductance is very low, about 10^{-5} siemens. It is also interesting to notice that, although the TDPPC signal decays rapidly, it is still positive (conductance increases upon illumination), whereas the only effect of light a.t 10 K is the decreasing conductivity (negative photoconductivity) in region near 560 nm. This beliavior raises ths question: Is there a transition temperature?

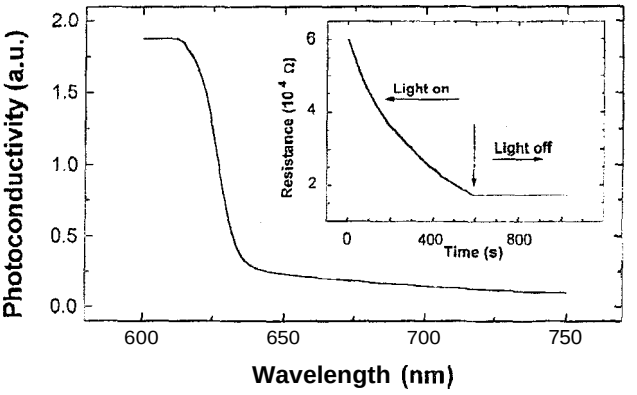

Figure 3: Photoconductivity spectrum for direct bandgap $Al_xGa_{1-x}As$ at ≃ 10 K. Inset - Illumination of this sample proceeds until 600 seconds with a 560 nm rnonochromatic light, then light is turned off and the coiiductance remains constant (T ≃ 10 K).

The observed behavior shown in Fig. 4, with a minimum in the photoconcluctivity about 565 nm suggests a possibility: if the bandgap is estimated according to the relations given by Lee at al[17] and assuming that the temperature correction for the L valley is the same

used for GaAs[16], the lowest conduction band minima yield transitions of about 560 nm for the L valley and 590 nm for the X valley. Then, the observed minumum is between these two minima, suggesting that the L valley effective mass state, as shown in Fig. 1, could have some participation. In this case a possible explanation is that electrons are excited from the valence band to this L valley effective mass state, and the small number of electrons which are still populating the X valley recombine with the free holes created by the electronic excitation. Then neutral states are generated, and a less conductive situation is obtained.

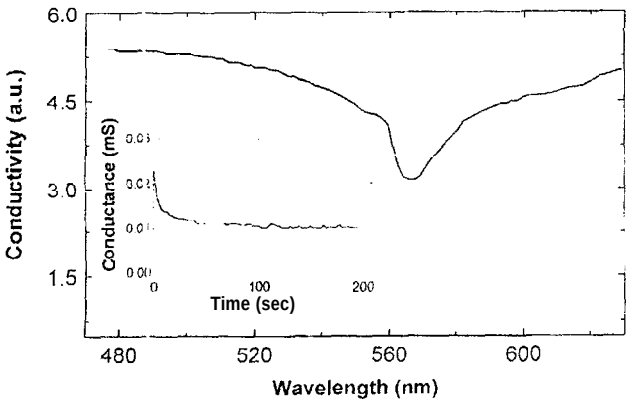

Figure 4: Conductivity under illumination for Si-doped $Al_{0.5}Ga_{0.5}As$ at $\simeq$ 10 K. The highest value is the conductivity in darkness. Inset - TDPPC for the same sample at 50 K, where subbandgap light is obtained with the help of a filter (RG715).

This hypothesis needs to be confirmed by further investigation, since the presence of additional states in indirect bandgap $Al_xGa_{1-x}As$ introduce several new possibilities for the striking observed results.

IV. Conclusion

Transient decay of persistent photoconductivity carried out for an indirect bandgap AlGaAs gives similar experimental results to those obtained for direct bandgap samples, in the range 80-100 K. All the attempts to fit these data using simple one channel models fail, as well as a model with an intermediate state located above the X valley minimum, which lead us to propose a new recombination model using double channel conduction and the participation of an L valley effective mass state. We obtain good fit using quite reasonable parameter values.

As the temperature is lowered below 60 K, PPC vanishes for indirect bandgap material, but not for direct bandgap material. Negative photoconductivity is obtained at 10 K for indirect bandgap material, where the conductivity decreases upon illumination in the region near 560 nm. We interpret these results in terms of the L and X valley effective mass states. The A_1 state cannot be identified by photoconductivity measurements. Further work is needed to clearly determine these states.

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