Trapping mechanism to account for persistent photoeffects in heavily doped GaAs/AlGaAs multiple quantum wells

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(Received 6 November 1995; accepted for publication 22 January 1996)

We have investigated trapping mechanisms responsible for the persistent photoeffect in heavily doped $GaAs/Al_{0.3}Ga_{0.7}As$ multiple-quantum-well structures. The study was performed using infrared-absorption techniques to study the intersubband transitions of the wells as a function of secondary illumination. The frequency of the secondary illumination was varied by the use of filters on the secondary source. The peak energies of the intersubband transitions can be modeled using the nonparabolic anisotropic envelope-function approximation, which accounts for many-body effects due to the high doping level. The red shift in the intersubband transition energy observed on secondary illumination indicates a decrease in the carrier concentration in the wells due to trapping in the barrier. We have found a decrease in the strength of the persistent photoeffect when the energy of the photons used in the secondary illumination is below the band gap of Si (1.172 eV). This observation is consistent with optically activated traps whose activation energy is $\geqslant$1.172 eV. These data, along with temperature recovery data, make the most probable candidate for the trap the *DX* center. © *1996 American Institute of Physics.* [S0021-8979(96)03909-0]

INTRODUCTION

There has been increasing interest lately in the intersubband transitions of III–V multiple-quantum-well structures, mainly due to their applicability as long-wavelength infrared detectors.[1–10] $GaAs/Al_xGa_{1-x}As$ multiple quantum wells have been studied for application in the 8–12 μm spectral region. Photon absorption in this type of detector is due to electrons making transitions between different ''subbands'' in the conduction band of the material. The subbands are a consequence of the electrons being confined to the GaAs region of the material. The electrons are introduced into the conduction band by doping with a donor species such as Si.

Recent work[11,12] has explained the observed blueshift in the intersubband transition energies with increasing electron concentrations, and has observed transitions not only between ground and excited subbands, but also between excited subbands. It was found that in order to accurately model the intersubband transitions of heavily doped quantum wells, several many-body effects must be included. In particular, exchange, direct Coulomb, exciton, and depolarization interactions must be considered. When all of these interactions are considered, one observes an increase in the subband energies with increasing carrier concentration in the well. The spacing between the subbands also increases with increasing carrier concentration, resulting in a blueshift in the observed absorption with increasing carrier concentration. An additional effect is an increase in the linewidth of the absorption with increasing carrier concentration.[13,14] Ionized traps in the barrier may also affect the intersubband absorption, but the effect is small in comparison to the above-mentioned many-body effects. Persistent photoeffects on the intersubband transitions have also been observed.[15] The effect is seen as a red shift in the energy of the intersubband transition, indicative of a decrease in carrier concentration. The decrease has been postulated to be due to electron traps in the barrier. In this article we report results of measurements on the dependence of the electron trapping on the energy of the photons used for the persistent photoeffect. The results support the *DX* center as the electron trap.

EXPERIMENT

The sample used was a 100 period superlattice consisting of a 75-Å-thick layer of GaAs, and a 100-Å-thick layer of $Al_{0.3}Ga_{0.7}As$ which is uniformly doped with Si at a concentration of 1×10^{19} cm^{-3}. The structure was grown by molecular-beam epitaxy on a semi-insulating GaAs substrate. Self-consistent calculations[15,16] indicate that there are two subbands inside the well, and a resonant state just outside the well, with the Fermi level just above the second subband.

Infrared-absorption measurements were made in the frequency range of 500–2000 cm^{-1} using a BOMEM DA3.01 Fourier transform spectrometer. The infrared beam was incident on the sample at Brewster's angle in order to have a component of the incident electric field parallel to the growth direction of the wells. The sample was cooled to a temperature of 6 K using a continuous-flow liquid-helium cryostat. The resolution of the spectra obtained was 0.24 cm^{-1}.

Secondary illumination of the sample was provided by a 5 W quartz–halogen light bulb. The frequency output of the secondary source extended from the visible into the infrared. In order to study the dependence of the photoeffect on the frequency of the secondary source, a set of semiconductors were used as filters. The semiconductors acted as low pass filters, allowing frequencies below the band gap to illuminate the sample, while absorbing frequencies above the band gap. The filters used, along with their band gaps at room temperature, are listed in Table I.

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TABLE I. Filter materials used for secondary source.

Filter material	Band gap (eV)
GaAs	1.498
InP	1.405
Si	1.172

RESULTS

The infrared-absorbance spectrum of the sample prior to any secondary illumination is shown in Fig. 1. The spectrum was obtained at a sample temperature of 6 K. Two peaks at frequencies of 1157.2 and 960.9 cm^{-1} are clearly visible. The frequencies of the two peaks were determined by nonlinear least-squares-fitting procedures using Lorentzian peaks, and a nonlinear base line. The increasing base line with decreasing frequency is due to phonon absorption in the GaAs substrate. Self-consistent calculations which include many-body effects reveal that the peak at 1157.2 cm^{-1} corresponds to the transition between the ground subband and the first excited subband in the well (E_{12}). The peak at 960.9 cm^{-1} corresponds to the transition between the first excited subband of the well (E_{23}) and the resonant state just outside the well. The transition between the ground subband and the resonant state is allowed, but has an extremely low transition probability. Similar spectra have been observed in samples with slightly lower doping.[12]

Illuminating the sample with visible light while it is cold causes a very noticeable change in the absorbance spectrum. The spectrum of the sample after it was illuminated with a quartz–halogen source for 1 min at a temperature of 6 K is shown in Fig. 2. The illumination time was determined by observing no further change in the spectrum upon additional illumination. Curvefitting reveals that two peaks are still present, but with shifted frequencies. Both peaks are shifted to lower frequencies, with the higher-frequency peak exhibiting a larger shift. This is due to increased many-body effects for energy levels inside the well. These results are consistent with a decrease in the carrier concentration in the well. Similar results have been previously observed.[15] The interpretation of this result is that carriers are ionized from the well by the secondary source, and are trapped in the barrier.

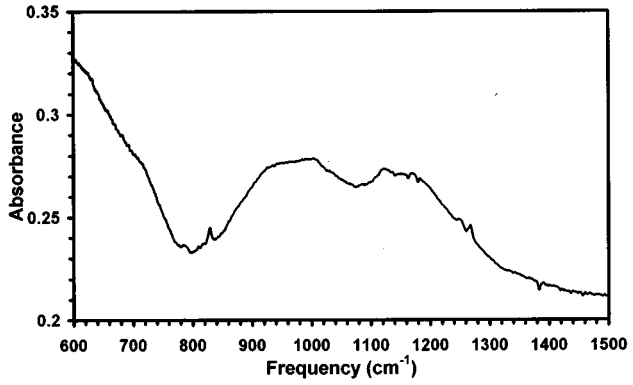

FIG. 1. Spectrum of sample prior to secondary illumination. Sample temperature was 6 K.

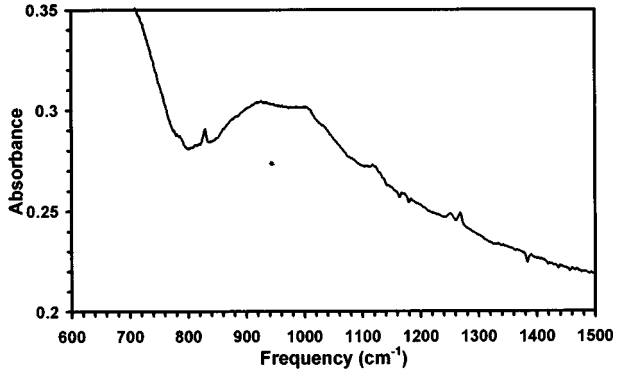

FIG. 2. Spectrum of sample after secondary illumination for 1 min with unfiltered quartz–halogen source. Sample temperature was 6 K.

In order to better understand the energetics of the traps, filters were placed over the secondary source in order to limit the energy of the photons incident on the sample. Spectra prior to and after illumination by the filtered secondary source were obtained while maintaining a sample temperature of 6 K. Because the incident intensity of the filtered source was smaller, longer illumination times were used (~2 min). Again, the illumination time was determined by illuminating the sample until no additional change in the spectrum was observed on further illumination. Spectra of the sample before and after illumination with the Si filtered source are shown in Figs. 3(a) and 3(b), respectively. Note that the change in the spectrum after illumination is much smaller than with the unfiltered source.

Similar spectra were obtained for the other two filters, and the peak positions before and after illumination were determined by nonlinear least-squares methods. In all cases, the peaks shift to lower frequencies. The shifts in the position of the two peaks for each filter are summarized in Table II.

DISCUSSION

Observed red shifts in the positions of the intersubband transitions can be used to calculate the decrease in the carrier concentration due to illumination by the secondary source. The model used employs many body interactions including depolarization and exciton shifts.[16] The results of the calculation are summarized in Table III.

It is interesting to note that the postillumination carrier density is highest for the unfiltered source, even though the intensity of the secondary source is highest in this configuration. The density is very similar for both the GaAs filter and the InP filter, but increases again when the Si filter is used. The initial assumption was that the intensity of the Si filtered source was lower than that of the other two filters. Calculations based on the frequency spectrum of the source and the transmittances of the filters show that this is not the case. The Si filtered source had the highest intensity, in fact.

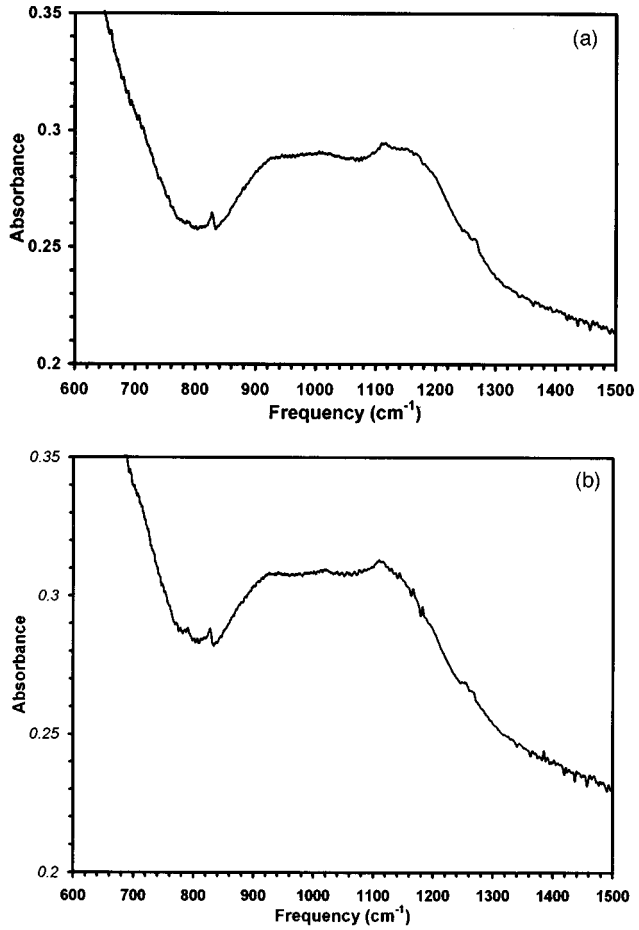

FIG. 3. (a) Spectrum of sample prior to secondary illumination. (b) Spectrum of sample after secondary illumination for 4 min with Si filtered quartz–halogen source. Both spectra were taken with sample at 6 K.

The interpretation of the data is based on the assumption that the carriers are being trapped by *DX* centers in the barrier. Si in AlGaAs is known to produce *DX* centers, which are known to trap electrons.[17] The fact that the unfiltered illumination produces the smallest effect can be interpreted as follows: The unfiltered light ionizes the carriers in the well, and they are trapped in the barrier. Some of the secondary light subsequently ionizes the traps, returning the carriers to the well. Reduction of the photon energy of the secondary source reduces trap ionization, allowing the traps to retain more carriers, with a corresponding reduction in the postillumination carrier density in the well.

The result for the Si filter still requires some explanation. Since the band gap of Si is still larger than the depth of the well (0.225 eV), the carriers are still ionized from the well by the Si filtered source. Apparently, they are not being trapped once they are ionized from the well. We postulate that the trapping by the *DX* centers is optically activated.

TABLE II. Frequency shifts for different secondary source filters. All values are ± 2 cm^{-1}.

Filter	ΔE_{12} (cm^{-1})	ΔE_{23} (cm^{-1})
None	20.4	3.5
GaAs	69.5	32.4
InP	76.4	43.0
Si	34.5	18.7

TABLE III. Carrier concentrations after secondary illumination. Values are based on a concentration of 1×10^{19} cm^{-3} prior to illumination.

Secondary source filter	Carrier concentration after illumination (10^{18} cm^{-3})
None	8.7
GaAs	5.6
InP	5.2
Si	7.8

The *DX* center has a Stokes shift of 0.82 eV between the thermal and optical ionization energies.[17] If we assume a similar shift in the trapping activation, we get an optically activated trapping activation energy of approximately 1.15 eV, based on the thermal activation energy of 0.33 eV.[17] This value is very close to the band gap of Si, so this would explain the result for the Si filtered secondary source.

The peculiar behavior of the *DX* center as an electron trap is due to the large lattice relaxation of the defect upon trapping an electron. In order for an electron to be trapped, it must overcome an energy barrier E_B. The height of this barrier for Si in AlGaAs is 0.33 eV.[17] At high temperatures ($>$150 K), this energy is supplied by phonons. At low temperature, however, there are not enough phonons present to trap an appreciable number of electrons, and the energy to overcome the barrier must be supplied by another means. In our case the energy is supplied by photons. The trapping process is illustrated schematically in Fig. 4.

Further evidence for the traps being *DX* centers comes from the temperature recovery of the persistent photoeffect. As the sample temperature is raised, the peak positions begin to shift to higher frequencies, and have returned to their original positions by the time the sample temperature reaches 150 K. This is the same temperature at which *DX* center

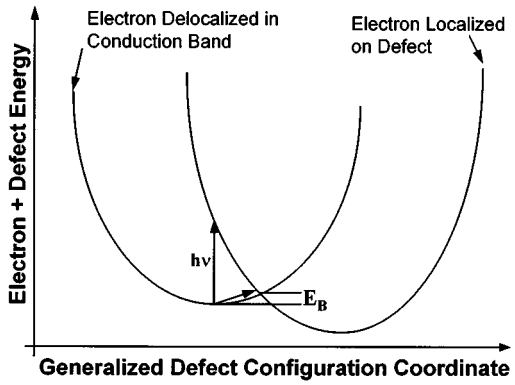

FIG. 4. Schematic representation of optically activated trapping by a *DX* center in terms of a configuration coordinate diagram. The energy barrier that the electron must overcome is indicated. Optically activated trapping is represented by the vertical arrow. Thermally activated trapping is represented by the diagonal arrow.

recovery occurs.[18] This result is in good agreement with previous results.[15]

CONCLUSION

We have observed the persistent photoeffect in heavily doped GaAs/$Al_{0.3}Ga_{0.7}As$ multiple quantum wells for differently filtered secondary sources. Unfiltered light induces the smallest decrease in carrier concentration due to the fact that carriers that are trapped by *DX* centers in the barrier are reionized back into the well by the secondary source. Intermediate energy filters (GaAs and InP) induce the largest decrease in carrier concentration. Once the cutoff energy of the filter is below a certain energy, trapping by the *DX* centers is no longer optically activated. We are able to place a lower limit of 1.172 eV on the activation energy for optically activated trapping by the *DX* center.

ACKNOWLEDGMENTS

The authors wish to thank Dr. M. O. Manasreh for helpful discussions, and gratefully acknowledge support by Sam Houston State University.

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