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Persistent Photo-conductance and Photoquenching of Selectively Doped $Al_{0.3}Ga_{0.7}As$ GaAs/Heterojunctions

M. I. Nathan, T. N. Jackson, P. D. Kirchner, E. E. Mendez,
G. D. Pettit, and J. M. Woodall
I.B.M. Thomas J. Watson Research Center
Box 218, Yorktown Heights, New York 10598

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The dependence on photon energy of the persistent photoconductivity (PPC) in selectively doped high mobility $Al_{0-3}Ga_{0.7}As$—GaAs heterostructures has been measured at temperatures below 80 K. A decrease in conductivity due to light exposure at one wavelength after exposure to light at another wavelength — photo-quenching — is also found. It is concluded that deep centers in GaAs and AlGaAs other than the DX center in AlGaAs are mainly responsible for PPC.

Key words: persistent photconductivity, AlGaAs, GaAs, heterojunctions

Very high electron mobilities μ_{nc} have been found in the channel between $Al_xGa_{1-x}As$ - GaAs hetero-junctions in which the $Al_x Ga_{1-x}As$ is heavily doped n-type and the GaAs is undoped or lightly doped — selectively doped heterostructures.[1-4] It has also been found that at low temperatures μ_{nc} and the density of electrons in the channel N_c are substantially increased when the structures are illuminated with white light.[2,5] Moreover, most of the increase in μ_{nc} and N_c persist for indefinite periods of time when the light is turned off for T $\lesssim$ 77 K. This phenomenon has been termed persistent photoconductivity (PPC). Drummond et al.[5] have studied Hall effect as a function of temperature in samples with unexposed $\mu_{nc} \simeq 10^5 cm^2/V$ sec at 77 K and have found that the decrease of PPC with increasing temperatures is similar to that for the DX[6,7] center in $Al_xGa_{1-x}As$ and suggested that the DX center is responsible. Tanoue and Sakaki[8] have studied the wavelength dependence of the rate of increase of PPC at 77 K in samples with unexposed $\mu_{nc} \approx$ 30,000 cm^2/V sec. They find that the phenomenon does not occur for light with photon energy hν below 0.8 eV. Above energies 0.8 eV they find N_c and μ_{nc} increase with secondary thresholds (ie. increases of rate) at 1.3eV and 1.9eV. They suggest that there is difficulty with the interpretation that the trap responsible for PPC is the DX center in $Al_xGa_{1-x}As$.

In this communication we report measurements of the spectral dependence of the PPC. The data generally confirm those of Tanoue and Sakaki[4]. However, we show that Tanoue and Sakaki's results depend on the detailed method in which the data is taken. In addition we present results on the spectral dependence on the terminal value of the PPC. We also report infrared-quenching of the PPC (i.e., once the sample has been put into a high conductance state, longer wavelength radiation causes it to go to a lower conductance state). The results indicate that the PPC is due to either macrosocopic fields or trap centers other than the DX center. It appears that traps are present both in the GaAs and AlGaAs.

The samples were grown by molecular beam epitaxy (MBE) at 610 C on high resistivity ($>10^7 \Omega$cm) undoped liquid encapsulated Czochralski substrates obtained from Microwave Associates, Burlington, Massachusetts. They consisted of 2.5μm buffer layer of undoped GaAs followed by 80Å of undoped $Al_{0.3}Ga_{0.7}As$, then 300Å of $Al_{0.3}Ga_{0.7}As$ doped with Si $1.4 \cdot 10^{18}$ cm^{-3}, capped by 35Å of $2 \cdot 10^{18} cm^{-3}$ Si doped GaAs. Hall effect and photoconductivity were measured on plotolithographic van der Pauw samples from two separate identically grown layers. The Hall effect data at

77 K is shown in Table I for a typical sample.

Table: Hall Effect at 77 K

	μ_{nC} cm^2/V-sec	N_c 10^{11} cm^{-2}
BEFORE EXPOSURE TO WHITE LIGHT	22,000	1.2
AFTER EXPOSURE TO WHITE LIGHT	106,000	5.8

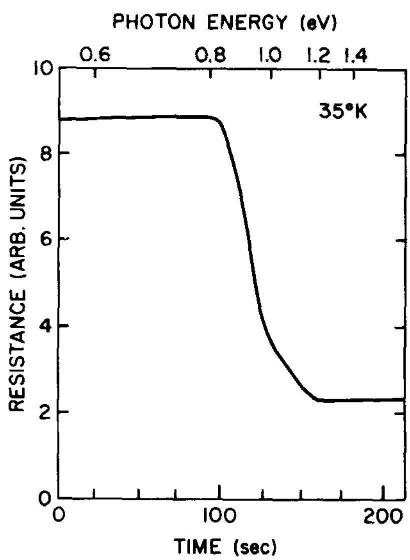
The sample was cooled from room temperature to 80 K or slightly below in the dark and then exposed to light from a monochromator as the photon energy was increased with time. The monochromator used had a CaF_2 prism with a tungsten bulb source. The sample is very sensitive to light with higher photon energy particularly above the energy gap of GaAs. Therefore extreme care was taken to eliminate photons with higher energy than the probe energy with the use of filters. With a filter eliminating all $h\nu > 0.75$eV no change in sheet resistance with time was observed to less than 2%. Fig. 1a shows the resistance vs. time as the photon energy was swept toward higher photon energies with the sample at 35 K and with a 1.28 eV low pass filter in the beam. The sample had not previously been exposed to light. The threshold for PPC can be seen at 0.82eV in agreement with Tanoue and Sakaki. The threshold is independent of temperature between 35 K and 85 K.

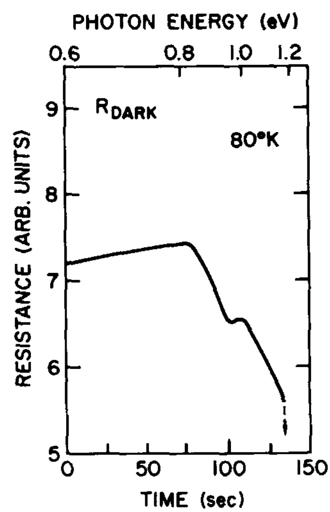
The shoulder barely visible in Fig. 1a can be enhanced if the sample is run under somewhat different conditions. In Fig. 1b the sample is again run from low to high photon energies as a function of time on the lower abcissa. Now, however, the sample was exposed to light between 0.82 and 1.28eV for a short period prior to the run so that the resistance was reduced by 20% from the dark value indicated by R_{DARK}. It can be seen that below 0.82eV the threshold in the dark resistance increases with time. This is a kind of quenching. However it is not necessary to simultaneously

Fig. 1. Resistance vs. time as the photon energy is swept to higher energy as indicated by the top scale. The slit width is 100 μm for CaF_2 prism in a Perkin-Elmer model 98 monochromator.

1a.
35 K sample previously unexposed.

1b.
80 K previously exposed so as t reduce resistance from its dark value, R_{DARK}, by 10%





illuminate the sample with greater than band gap radiation. If the sample is exposed to light of a given photon energy, light of a lower energy will cause the resistance to increase with time. In the dark the resistance of the sample is constant after exposure to light of less than the energy gap. The peak at 1.0eV represents an increase of resistance with time. Similar effects have been observed in this photon energy range in bulk high resistivity GaAs containing oxygen and chromium, by Lin et al.[9] This peak was not reported by Tanoue and Sakaki.

For light with $h\nu<1.42$eV (room temperature GaAs filter) the conductance increases further. However in order to reach the maximum conductance it is necessary to expose the sample to light with $h\nu>1.52$eV (the energy gap of GaAs at low T). No further increase in final conductance was observed at higher photon energies. This result is shown in Fig. 2. However an increase in the rate of reaching the final value was observed at 1.9eV, which is close to the energy gap E_g for $Al_{0.3}Ga_{0.7}As$.

The change in resistance with time under less than energy gap illumination was followed to completion at 1.2eV. This process took about two hours. The result is shown in Fig. 2 plotted as the 0 at 1.2eV. At lower photon energies the approach to equilibrium had not been reached even after 3 hours of observation. After 3 hours exposure at 1.0eV the conductance was 0.15 in Fig. 2 but it was still increasing.

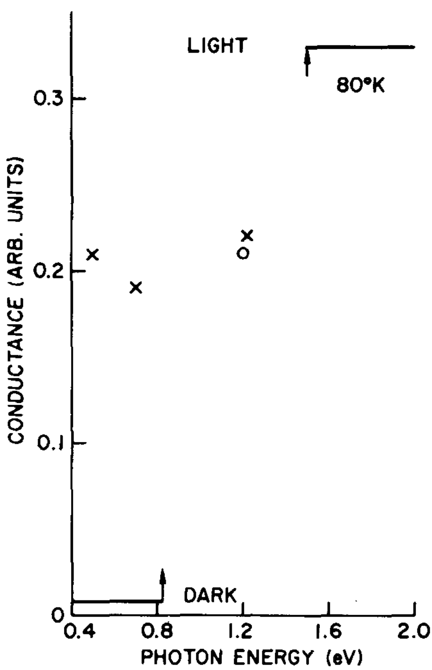


Fig. 2.
Conductance vs. photon energy. The low value applies for photon energies <0.82eV. The high value is after exposure to $h\nu \gtrsim 1.5$eV. In between the conductance depends on the history light exposure. The X's are after exposure to $h\nu > E_g$(GaAs) then exposure at the $h\nu$ where they are plotted. The o is the final conductance after exposure only to 1.2eV light.

If, after exposure to $h\nu > E_g$ (GaAs) the sample is left in the dark until the transient photo-conductivity decays (about 3 minutes) and then exposed to $h\nu < E_g$(GaAs) the sample conductance is reduced with time for times as long as one hour. This photoquenching also persists when the light is turned off, that is, the conductance is stable in the dark. Fig. 2 shows the final value of conductance at three different hν plotted as x's. It can be seen that approximately 40% of the photo-conductance can be quenched by the light with $h\nu<E_g$ and the value of the quenched conductance is approximately independent of hν.

The spectral dependence of the PPC of thick AlGaAs layers has been studied by Collins et al.[11]. Their results differ substantially from ours and Tanoue and Sakaki. They observe a threshold at 0.6eV, and no increase at the E_g of GaAs or AlGaAs. However on the basis of experiments in which they etched the sbustrate they conclude macroscopic fields are involved in the PPC in agreement with results of Matsumoto et al.[12]. We also agree with the conclusions.

One can draw the following inferences from the experimental results presented above.

1) The DX center is not totally responsible for the PPC, if at all. Lang and Logan[10] reported appreciable (10^{-3} of its peak value) optical cross section of 1.0eV whereas we observe a threshold of 0.82eV. Moreover, infrared quenching was not found for DX centers in $Al_xGa_{1-x}As$, whereas we do observe it.

2) The fact that hν must be greater than E_g(GaAs) to obtain the maximum conductance suggests that macroscopic fields are separating electron hole pairs as found by Theodorou and Queisser[13] in GaAs structures.

3) A possible cause for the infrared quenching is that electrons are excited out of the channel by free electron absorption. The lack of dependence on hν suggests that these cross the barrier into $Al_{0.3}Ga_{0.7}As$ where they are retrapped.

It appears that trapping in both the GaAs buffer layer and the $Al_{0-3}Ga_{0.7}As$ contribute to the persistent photo-conductivity in selectively doped AlGaAs—GaAs heterostructures. Unidentified deep centers usually present in high resistivity material are involved.

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