The persistent photoconductivity effect in modulation Si δ-doped pseudomorphic $In_{0.2}Ga_{0.8}As/GaAs$ quantum well structure

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Persistent conductivity effect in modulation Si δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ quantum well (QW) structure grown by metal organic vapor phase epitaxy was examined using Hall effect and magnetotransport measurements in magnetic fields up to 12 T at $T=1.7$ K. No measurable electron density was found in the QW after cooling down the sample in the dark and the electron density in the *V*-shaped δ-doped potential well (V-QW) of the modulation Si δ-doped layer was two times lower than the electron density of the same Si δ-doped layer in GaAs. The illumination resulted in the increase of electron density in the V-QW at the beginning and consequently in the population of the ground subband in the InGaAs QW. Due to parallel conduction, a nonmonotonic dependence of Hall density as a function of illumination time was observed. The total electron density in the modulation doped InGaAs/GaAs heterostructure after the illumination became approximately equal to the electron density in the Si δ-doped layer in GaAs. *© 1997 American Institute of Physics.* [S0003-6951(97)01438-1]

The $In_{1-x}Ga_xAs/GaAs$ semiconductor heterostructures have attracted considerable attention of researchers due to their promising applications to high speed electronic devices.[1] The device performance, e.g., in high electron mobility transistors (HEMTs), can be further improved by using the δ-doping instead of the conventional modulation bulk doping technique.[2] Several reports on the transport properties of modulation doped $In_{1-x}Ga_xAs/GaAs$ have been published recently.[3–7] The interplay between two-dimensional electron gases (2DEGs) confined in quantum well (QW) and in *V*-shaped potential well (V-QW) formed in the Si δ-doping layer is one of main interests.[8,9] The illumination had usually been used to change the electron density in modulation doped heterostructures, such as AlGaAs/GaAs systems. The *DX* centers are responsible for persistent photoconductivity effect (PPC) in AlGaAs/GaAs heterostructures.[10] By comparison, the origin of a weak PPC effect observed in Si δ-doped GaAs is still under debate.[11–14]

In this letter, the transport properties of modulation Si δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ QW structure were investigated in the dark and after subsequent illumination. The aim of our work was to examine the PPC effect on the Si δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ QW structure.

The Si δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ QW structure was grown by low pressure (76 Torr) metal organic vapor phase epitaxy (MOVPE) at 630 °C. The details of the growth procedure were published previously.[6] The schematic sample structure is shown in Fig. 1. The top 5 nm of the GaAs cap layer was slightly doped to 2×10^{17} cm^{-3}. A Si δ-doped layer was introduced in the back GaAs barrier 10 nm from the QW. The electron density of the same Si δ-doped layer in GaAs measured at room temperature by means of electrochemical capacitance–voltage profiling was equal to 23×10^{11} cm^{-2}. Transport measurements were performed in an Oxford SM2000 cryostat with a superconducting coil at $T=1.7$ K in magnetic fields up to 12 T. The photolithographically defined Hall-bar structure with Au/Ge annealed contacts was used. The PPC was obtained by illumination of a sample at $T=1.7$ K with an infrared ($\lambda=906$ nm) light emitting diode mounted outside the cryostat.

A set of magnetoresistivity (ρ_{xx}) and Hall resistivity (ρ_{xy}) traces versus magnetic field is shown in Fig. 2. Presented curves were obtained under following conditions. The first measurement (see curve a in Fig. 2) was performed just after cooling down the sample in the dark. Next the sample was illuminated for a few seconds. It was found that after the illumination the ρ_{xx} decreased persistently. Then, the second measurement was performed in the dark (see curve b in Fig. 2). The same procedure (a few seconds illumination, measurement in the dark) was applied several times with the results shown in Fig. 2 (see curves c–k). All illumination periods resulted in persistent conditions, i.e., after the light was off, no resistivity transient could be observed. Further illumination (after the curve k in Fig. 2 was recorded) caused the unstable conditions. After the light was off, the sample resistivity increased with a characteristic time of minutes and with the saturation at the level of the last persistent conditions (curve k in Fig. 2). The measurement under continuous illumination was also performed (see curve l in Fig. 2).

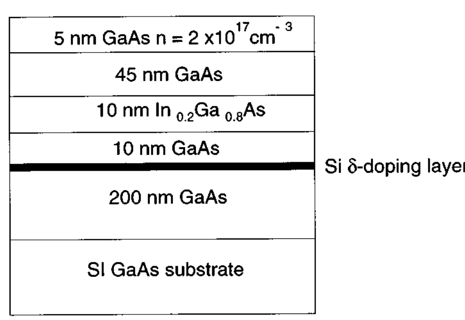

FIG. 1. The schematic structure of the investigated sample.

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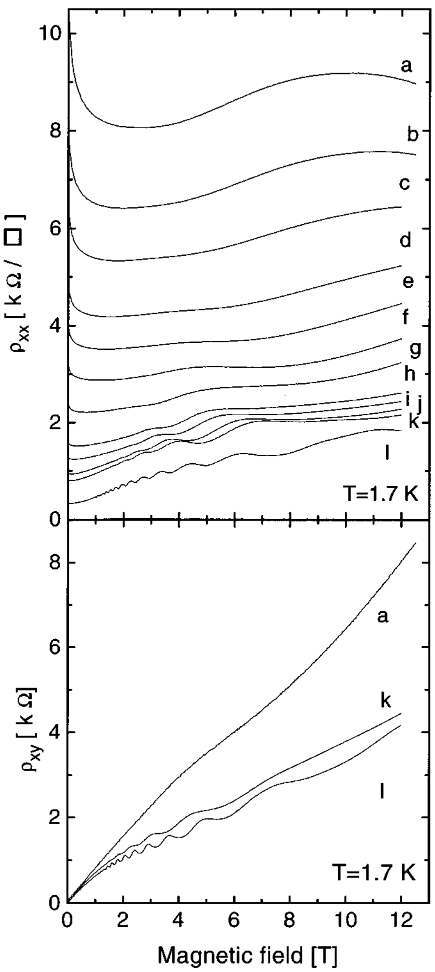

FIG. 2. Magnetoresistivity (ρ_{xx}) of the sample measured at $T=1.7$ K: just after cooling down in the dark (a), in the dark but after subsequent illumination periods (b–k), and under continuous illumination (l). Hall resistivity (ρ_{xy}) for measurements a, k, and l are also shown.

Clearly the shape of magnetoresistivity traces changed as a result of illumination. The Shubnikov de Haas (SdH) oscillations appeared after an illumination. The fast Fourier transform (FFT) was applied and the relevant spectra are shown in Fig. 3. It can be seen that sheet electron density was increasing gradually as a result of illumination. The electron Hall and sheet electron densities after subsequent illumination periods are in Fig. 4. It was found that Hall mobility was an increasing function of the total illumination time. The Hall electron density was a nonmonotonic function of the total illumination time (or of the Hall mobility, as in Fig. 4). Initial illumination resulted in the increase of the Hall density from 8.9×10^{11} to 14×10^{11} cm^{-2}. Further illumination however caused a decrease of the Hall density to 8×10^{11} cm^{-2}. The Hall density measured under continuous illumination was equal to 10.3×10^{11} cm^{-2}. Electrical parameters of our sample measured at room temperature and at $T=1.7$ K are summarized in Table I.

The nonmonotonic dependence of the Hall density on the illumination time can be explained using a two carrier conduction model. The resistivity of the 2DEG system can be described by the two-dimensional resistivity tensor ρ.[15] In case of a two carriers transport, the Hall density n_H and Hall

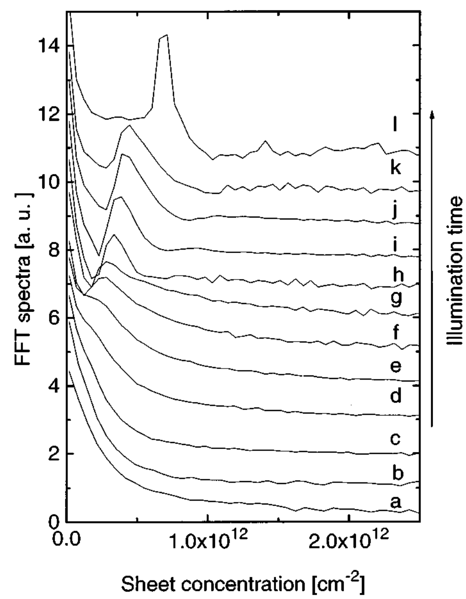

FIG. 3. The FFT spectra of magnetoresistivity (ρ_{xx}) traces shown in Fig. 2. Offset added for clarity.

mobility μ_H are functions of both carrier densities (n_1, n_2) and mobilities (μ_1, μ_2).

In the low magnetic field limit ($\mu_i B \ll 1$),

$$n_H = \frac{B}{e\rho_{xy}} = \frac{(n_1\mu_1 + n_2\mu_2)^2}{n_1\mu_1^2 + n_2\mu_2^2}, \tag{1}$$

$$\rho_{xx} = \frac{1}{e(n_1\mu_1 + n_2\mu_2)}. \tag{2}$$

It can be seen that the conduction in the low field region is dominated by the higher mobility carriers.

In the high magnetic field limit ($\mu_i B \gg 1$),

$$n_H = \frac{B}{e\rho_{xy}} = n_1 + n_2, \tag{3}$$

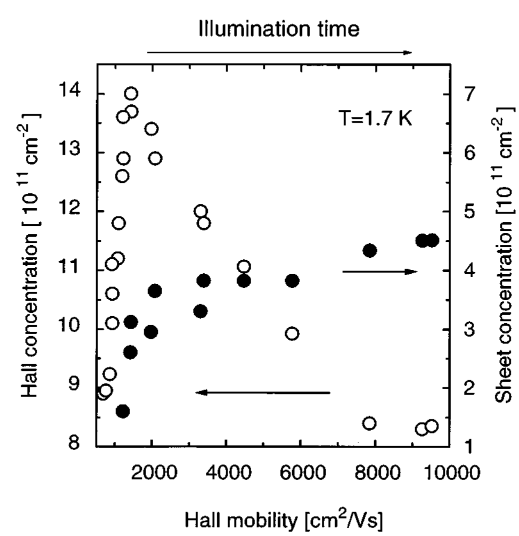

FIG. 4. The electron Hall density (open circles) and sheet electron density (full circles) obtained from FFT spectra of the ρ_{xx} traces as a function of Hall mobility. The Hall mobility increased monotonically with the total illumination time. Note different scales for both electron densities.

TABLE I. Summary of the electrical transport parameters: Hall density—n_H, Hall mobility—μ_H, and sheet electron density—n_{SdH} in the modulation Si δ-doped pseudomorphic $In_{0.2}Ga_{0.8}As/GaAs$ QW.

	300 K	1.7 K in the dark	1.7 K in the dark after an illumination	1.7 K continuous illumination
$n_H[10^{11}\ cm^{-2}]$	7.2	8.9	8.0	10.3
$\mu_H[cm^2/V\ s]$	2720	760	9520	18750
$n_{SdH}[10^{11}\ cm^{-2}]$	⋯	⋯	4.5	7

$$\rho_{xx}=\frac{n_1/\mu_1+n_2/\mu_2}{(n_1+n_2)^2}. \tag{4}$$

The Hall density equals the sum of both carriers densities and the longitudinal resistivity ρ_{xx} is governed by lower mobility channel.

Just after cooling down a sample in the dark, the Hall resistivity ρ_{xy} of our sample was a near-linear function of magnetic field. It suggests that only one type of carriers was present (see Fig. 2). Very intensive negative magnetoresistivity effect[16] in the ρ_{xx} trace can be observed with no SdH oscillations. A low mobility of carriers ($760\ cm^2/V\ s$) at a low temperature is predominantly an effect of the large density of ionized centers. This fact suggests that electrons are spatially confined in the Si δ-doped layer due to a deep *V*-shaped potential well and the electrostatic attraction of electrons to ionized Si donors. During the illumination, photogenerated electrons are first transferred to the V-QW but not to the InGaAs QW. This causes an increase of the Hall density and the Hall mobility. Further illumination results in gradual population of the ground electron subband within the QW. Due to the much higher mobility of electrons in the QW, the SdH oscillations can then be observed. Two carrier conduction takes place, which induces a nonlinear field dependence of the Hall resistivity (ρ_{xy}) (see curve k in Fig. 2) and the magnetoresistivity (ρ_{xx}) saturation at higher magnetic fields. It results also in the decrease of the Hall density. Under persistent conditions, the Hall mobility reached $9520\ cm^2/V\ s$, with the electron sheet density found from the FFT equal to $4.5\times10^{11}\ cm^{-2}$. The total electron density found from a slope of ρ_{xy} in the region of the highest magnetic fields was equal to $19.3\times10^{11}\ cm^{-2}$, which gives the electron density within the V-QW equal to $14.8\times10^{11}\ cm^{-2}$. The transport mobilities in the QW and the V-QW found from those values are equal to 12 450 and $1360\ cm^2/V\ s$, respectively. The increase of electron mobility in the V-QW resulted from the increase of the electron density with the ionized Si atoms density unchanged.[17] Under continuous illumination, the sheet density increased to $7\times10^{11}\ cm^{-2}$ with the Hall parameters of $n_H=10.3\times10^{11}\ cm^{-2}$ and $\mu_H=18\,750\ cm^2/V\ s$.

The band bending in the investigated structure resulted in the total depletion of the QW after cooling down a sample. The interesting question to our findings is the origin of electrons released after an illumination. The total electron density after an illumination was $19.3\times10^{11}\ cm^{-2}$ as compared with electron density of the same Si δ-doped layer in GaAs ($23\times10^{11}\ cm^{-2}$). In our opinion, photogenerated electrons come from the ionized Si centers of the doping plane. They are trapped on deep centers within the structure at room temperature and they cannot be seen at low temperature in the dark. Illumination releases electrons from those centers. Due to the potential barriers of the QW and the V-QW, electrons cannot return to deep centers. In such a picture, deep centers do not have to possess the potential barrier (as DX centers do) because they are separated spatially from both wells. The fact that the V-QW is being populated first suggests that the centers in question are very likely interface states.

In conclusion, the transport properties of modulation in Si δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ QW structure were examined. It was found that after cooling down the sample in the dark, the ground electronic subband within the QW was empty and the conduction took place in the V-QW. The PPC effect resulted in the gradual filling first of the V-QW and then the QW. The nonmonotonic behavior of the Hall electron density as a function of the total illumination time due to the parallel conduction in V-QW was found. The total electron density after an illumination was approximately equal to the electron density in the Si δ-doped GaAs. It has been proposed that the photogenerated electrons originate mainly from ionized Si atoms of the doping plane, they are captured on deep centers within the structure and released at low temperatures by illumination.

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