Positive and negative persistent photoconductivity in a two-side-doped $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum well

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(Received 7 December 1998)

We present detailed studies of the persistent photoconductivity effect in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum well, including wavelength, temperature, and time dependencies. We found conclusive results that show competition between the positive and negative persistent photoconductivity effects. We suggest that a complete understanding of the decay and buildup kinetics in the entire temperature region must incorporate both the positive and negative effects. We conclude that the major positive effect is due to the band-to-band electron-hole generation in the well layer followed by the spatial charge separation and the negative effect is related to the pumping of the two-dimensional electrons into the doped barrier layer followed by the decrease of mobility. [S0163-1829(99)03443-8]

I. INTRODUCTION

The $In_xGa_{1-x}As$ based heterostructures are of great interest for high speed and optical devices. Especially when they cover the 1.3 to 1.6 μm wavelength which is the low loss and low dispersion region of optical fiber communication. Furthermore, they have many superior electrical and optical properties, such as higher electron mobility, larger conduction-band discontinuity, and lower electron effective mass, etc. than those of the GaAs system. Thus considerable experimental and theoretical effort has been made towards the understanding of the electrical and optical properties of the $In_xGa_{1-x}As$ based heterostructures. The effect of persistent photoconductivity (PPC) has been reported in this material system.[1] However, the experimental result is incomplete, and the underlying mechanism is still not clear. PPC effect is photoinduced conductivity that persists for a very long period of time after the termination of the photoexcitation. This effect has been observed in many semiconductor materials.[2–6] Many basic physical processes in semiconductors can be studied by this phenomenon such as the optical excitation, transport, storage, and relaxation of charge carriers. In this paper, we present a detailed study of the PPC effect in an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure. Depending on the experimental conditions, the heterostructures can exhibit positive or negative persistent photoconductivity effect. Based on the studies of the dependencies on energy of excitation, temperature, and time, the underlying mechanism of the PPC effect is proposed to explain all our observation.

II. EXPERIMENT

We performed our measurements upon an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure that is two-side doped with silicon. It was grown by molecular-beam epitaxy on an InP(100) substrate. A superlattice consisting of ten periods of 50/50-Å-thick $In_xAl_{1-x}As/In_xGa_{1-x}As$, was grown on the substrate followed by an undoped 2500-Å-thick $In_xAl_{1-x}As$. The following sequence of the modulation-doped structure includes a Si-doped 50-Å-thick $In_xAl_{1-x}As$ layer, an undoped $In_xAl_{1-x}As$ spacer of thickness 150 Å, a well layer made up of 100-Å $In_xGa_{1-x}As$, an undoped $In_xAl_{1-x}As$ spacer of thickness 120 Å, a Si-doped 200-Å-thick $In_xAl_{1-x}As$, and a Si-doped 80-Å-thick $In_xGa_{1-x}As$. The two-dimensional electron gas is confined in the $In_xGa_{1-x}As$ well layer. From Hall measurements, the mobility is 5.0×10^3 cm^2/V s at 300 K, 1.89×10^4 cm^2/V s at 77 K, and the carrier concentration is 3.3×10^{12} cm^2 at 77 K. For the PPC measurement a Halogen lamp was used as the light source. A monochromator and an appropriate filter were used to obtain the right photon energy as desired. Ohmic contacts were formed by indium alloying on the sample surface. The sample was attached to a copper sample holder, which is inside a closed-cycle He refrigerator, with care taken to ensure good thermal contact yet electrical isolation. The bias voltage was supplied and measured by a Keithley 236 source measure unit. The low excitation level was carefully kept to ensure the dominance of PPC. The data obtained at different conditions were taken in such a way that after a measurement the system was gradually heated up to room temperature to recover the sample to its initial state and then cooled down again in the dark to the temperature of measurements. This is to ensure that the data obtained for each measurement has the same initial condition. Details of the PPC measurement procedure was similar to that described previously.[7]

III. RESULTS AND DISCUSSION

From our PC data and published reports,[1,8] the band gap of the $In_xGa_{1-x}As$ is about 0.81 eV and the $In_xAl_{1-x}As$ is 1.5 eV at 4.2 K. Thus we can examine the different photoconductivity effects from the different layers by using photoexcitatoin above or under the barrier energy gap.

A. PPC buildup transient

1. Above-barrier photoexcitation

Figure 1 presents the plot of PPC buildup curves obtained for the $In_xGa_{1-x}As/In_xAl_{1-x}As$ heterostructure at different temperatures. The energy of the excitation photon is fixed at 1.55 eV. The same photon dose was used for this set of data. The dark current has been subtracted out and the normalization is done by the final level C just before the termination of illumination. The curves obtained for the high-temperature region ($T>100$ K) and the low-temperature region display

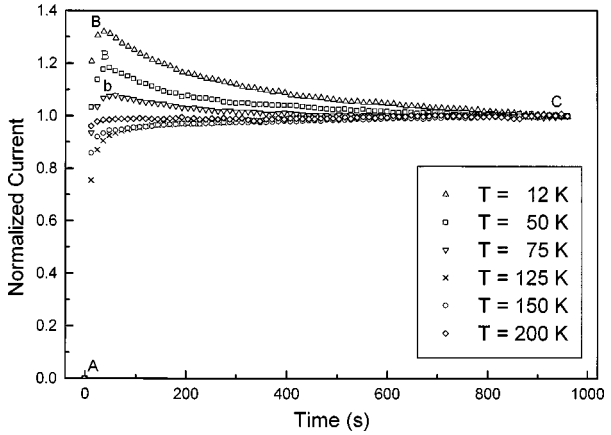

FIG. 1. PPC buildup curves obtained at different temperatures. The energy of the excitation photon is fixed at 1.55 eV, which is larger than the $In_xAl_{1-x}As$ band gap. The dark current has been subtracted out and the normalization is done by the saturation current just before the termination of illumination.

different features. At temperatures higher then 100 K, the buildup curves solely increase to their saturation level during buildup process. Yet, for those obtained lower than 100 K show a quite different shape. The light is turned on at *A*, and between *A* and *B*, these curves rise sharply in this small interval of time. Surprisingly, with the illumination kept turned on, the photocurrents begin to drop after passing *B*. Given sufficiently long time, these photocurrents would relax to an equilibrium level *C*. The critical temperature for the transition is about 100 K. We have to point out that the critical temperature shifts somewhat depending on the energy and the intensity of light. The observed PPC buildup curves are quite different from those obtained from the materials exhibiting only conventional photoconductivity, which has a typical transient response time on the order of 10^{-6} s.

2. Under-barrier photoexcitation

The buildup curves obtained for under-barrier photoexcitation also have a transition temperature around 100 K. But the distinction between the buildup curves obtained in the different temperature regions further intensifies for under-barrier photoexcitation. The buildup curves obtained in the high-temperature region ($T>100$ K) have the same behavior as that obtained for above-barrier photoexcitation. However, the buildup curves obtained in the low-temperature region display quite dramatic properties as shown in Fig. 2. After the light is turned on, the current increases sharply from the dark current level at *A* to a local maximum level at *B*, and then begin to decrease intensively to a lowest possible level *C*. Finally, it gradually increases with the illumination to the final level *D*. The light is turned off at *D*. Because of the low buildup rate from *C* to *D*, the real saturation was never achieved in our experiments. The drop from *B* to *C* decreases with the increase of temperature until it vanishes at some temperature. Such a drop in conductivity during illumination is termed as negative photoconductivity,[9–11] contrary to normal positive photoconductivity. The experimental results show that the positive photoconductivity effect dominates in the buildup process at temperatures above 100 K, while at temperatures below a critical value ($T_c\sim 100$ K in our study),

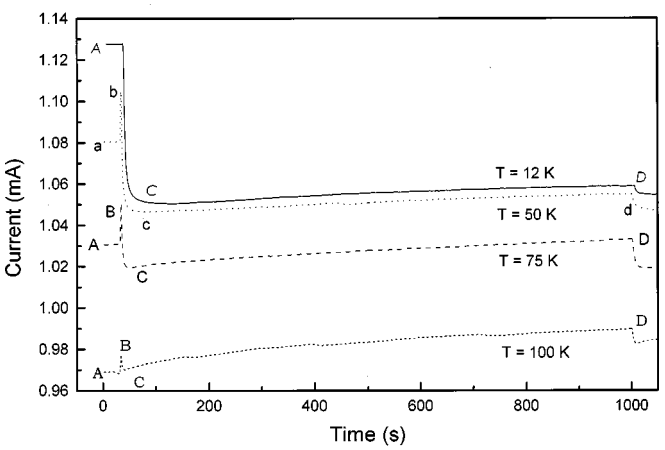

FIG. 2. PPC buildup curves for under-barrier photoexcitation of 0.99 eV obtained at temperatures under 100 K.

the negative photoconductivity effect plays a role and even attains dominance for temperatures lower then 50 K.

B. PPC decay

1. Above-barrier photoexcitation

The normalized decay curves obtained at different temperatures are shown in Fig. 3. We discovered that the whole temperature region can be divided into two regions according to the temperature dependence of decay rate. PPC decays slower with increasing temperature in the temperature region of 50 to 100 K. This is unexpected from the present existing PPC models. However, as temperature increases to above 100 K, PPC shows the usual behavior, i.e., the PPC relaxation rate increases as temperature increases. In the full time range, we found that the decay kinetics can be well described by the stretched-exponential function

$$I_{\mathrm{PPC}}(t)=I_{\mathrm{PPC}}(0)\exp[-(t/\tau)^{\beta}] \quad (0<\beta<1), \qquad (1)$$

where β is the decay exponent and τ is the decay time constant. $I_{\mathrm{PPC}}(0)$ is the buildup current at $t=0$, which is the moment the excitation is being terminated. Relaxation of disordered systems towards equilibrium often obeys such a time law which is not exponential. It can also be used to describe the PPC behavior due to *DX* centers in $Al_xGa_{1-x}As$.[3] The

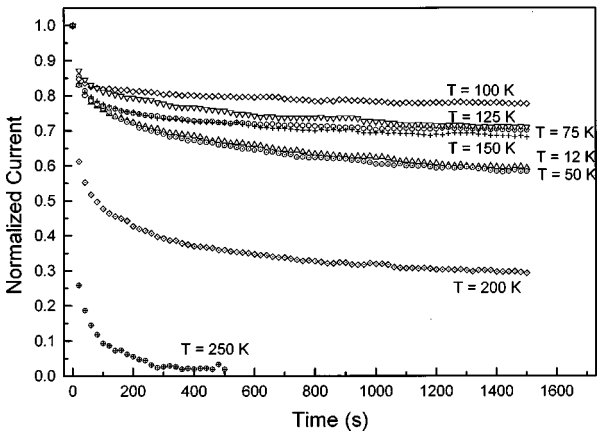

FIG. 3. PPC decay curves obtained at different temperatures. Each curve is normalized to unity at $t=0$, which is the moment that the illumination is terminated, and dark current has been subtracted out. The energy of the excitation photon is 1.9 eV.

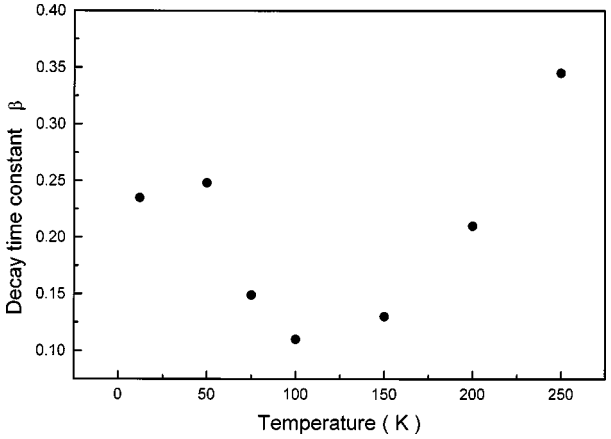

FIG. 4. Plot of the decay exponent β as a function of temperature. The same photon dose was kept. The energy of the excitation is 1.55 eV.

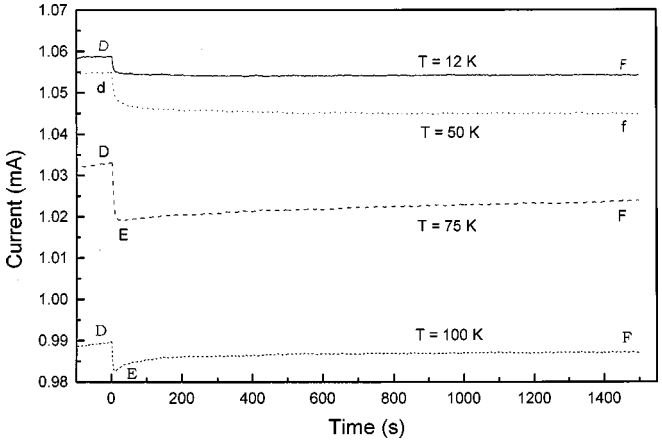

FIG. 6. Plot of decay curves in the temperature region $T<100$ K. The energy of the excitation photon is 0.99 eV.

plot of the decay exponent versus temperature is shown in Fig. 4. We found that it exhibits a curious V shape with central minimum at about 100 K. Figure 5 shows the plot of decay time constant as a function of temperature, and it shows a Λ shape with central maximum at 100 K. If we assume that in the region $T>150$ K, the decay process is thermally activated. The decay time constant τ for thermally activated recombination can be described by

$$\tau=\tau_0 \exp(E_c/kT), \tag{2}$$

where E_c denotes the carrier capture barrier, and τ_0 is a constant. The recombination barrier calculated in the region $T>150$ K is about 300 meV.

2. Under-barrier photoexcitation

For the condition of under-barrier photoexcitation the normalized decay curves obtained in the high-temperature region, $T>125$ K, exhibit stretched-exponential behavior and is consistent with Eq. (1). The decay time constant τ declines as temperature increases, and the decay exponent increases as temperature increases. The decay curves with photoexcitation of 0.99 eV in the low-temperature region are shown in Fig. 6. After the illumination is turned off at $t=0$, the current undergoes a sharp drop to a minimum at E. The long-term relaxation behavior depends on the temperature. The current increases in the temperature region of 75 to 100 K, and persists in decaying at temperatures below 50 K. It is worth pointing out that the final level F is even lower than the dark current level A (in Fig. 2) significantly at temperatures below 75 K. We thus confirm that the N PPC effect exists and dominates in the low-temperature region for the under-barrier photoexcitation.

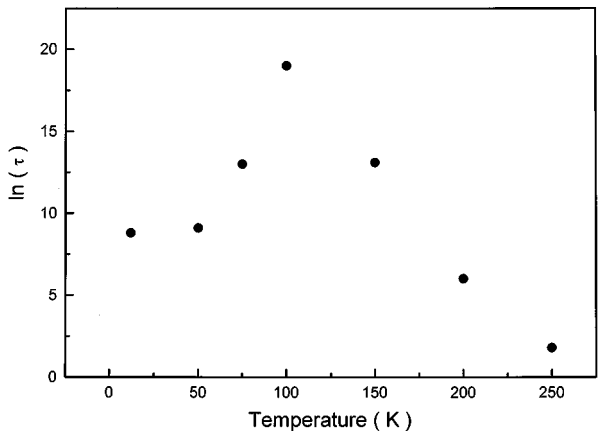

FIG. 5. Plot of ln τ vs temperature, where τ is the decay time constant. The energy of the excitation photon is 1.55 eV.

Our main results for the PPC effect in InAlAs/InGaAs quantum well can be summarized as follows.

1. *For above-barrier photoexcitation*. No negative persistent photoconductivity is found in the relaxation process for the entire temperature region investigated. However, the effect of negative photoconductivity plays a role in the buildup process at temperatures below 75 K.

2. *For under-barrier photoexcitation*. There exists a critical temperature T_c. The regime changes from negative PPC to positive PPC as temperature increases over T_c. In our studied sample, the transition is around 100 K. The negative photoconductivity is clearly observable at temperatures below 100 K and takes over dominance at temperatures below 75 K under illumination. The relaxation of negative photoconductivity can be seen in the temperature region of 75 to 100 K. Outside this region the relaxation of the negative effect becomes negligible. To our knowledge, this is the first observation of the coexistence of N PPC and PPC during illumination and both of them are truly persistent in our $In_xGa_{1-x}As/In_xAl_{1-x}As$ system.

C. Discussion

The positive PPC effect exists in both above-barrier and under-barrier photoexcitation. Thus it is related to the optical transition that takes place in the well layer only. Some previous studies had attributed PPC to defect trapping.[3,6] Defect-related physical processes that lead to negative PPC effect occurs only when photogenerated free electrons in the conduction bands in both barrier and well layers are captured by the defect centers. Under illumination, all the defect centers would soon become occupied, and the negative PPC effect would be saturated. Besides such an effect will appear more strongly in the above-barrier photoexcitation than in the under-barrier photoexcitation since the positive PPC occurs mainly in the well layer. However, this behavior is in contrast with our observation. Although defect trapping is often found to be the physical origin for the persistent photoconductivity effect, it is incapable of providing a thoroughly consistent view for our complex observations. In-

stead, we found that a model based on the competition between the excitation of a two-dimensional electron gas (2DEG) and spatial separation of photoexcited charge carriers could best explain all our experimental results. The physical process of the photoresponse of the observed PPC effects can be understood as follows.

(1) The initial sharp rise in conductivity in the buildup process is due to the band-to-band electron-hole generation in the barrier or well layer, depending on the photon energy, which is a fast process in nature.

(2) Afterward, the electrons are pumped from the 2DEG channel into the conduction band of both barrier layers accompanied by the decline of mobility. The conductivity is reduced provided that this effect is stronger than the band-to-band excitation. It explains why the dominant negative photoconductivity appears when the illumination is set to excite the well layer only and disappears when both the barrier and well layers are excited at the same temperature.

(3) The decrease of the electron density in the 2DEG channel smooths the band bending at interfaces and thus reduces the barrier due to the band bending. As a consequence, electrons in the conduction band of barrier layers tend to return to the 2DEG channel at a higher rate. The equilibrium between the pumping and returning of the 2DEG electrons is responsible for the true saturation of the buildup current.

Electrons return to the 2DEG channel from the conduction band of the barriers more quickly at higher temperatures. It accounts for the observation that the negative effect decreases as the temperature increases and finally it vanishes at some temperatures above 100 K. Hence the negative photoconductivity effect does not contribute in the buildup process at temperatures above 100 K.

(4) The conductivity drops rapidly for several seconds after the light is turned off because of the termination of the positive contribution due to the band-to-band electron-hole generation.

(5) Both positive and negative effects contribute to the photoconductivity we observed. At temperatures below 50 K, negative PPC decays slowly due to the lack of thermal energy and the relaxation is dominated by the positive PPC, which is due to the spatial separation of the photoexcited electrons and holes in the well. In the temperature region of 50 to 100 K, the process where electrons in the conduction band of the barriers are thermally excited and return to the 2DEG channel starts to play a role. It accounts for the observation that the conductivity increases slowly after the rapid decrease as shown in Fig. 6. Thus the rapid drop after removing the illumination is the only observable effect that comes solely from the positive photoconductivity in the temperature region where the relaxation is dominated by the negative PPC.

(6) We suggest that a full understanding for the temperature dependence of the decay parameters obtained for above-barrier photoexcitation must also incorporate the negative PPC effect, although it never reaches dominance in the overall photoresponse.

According to the above model, we know that at low temperatures ($T<100\,\mathrm{K}$), negative PPC plays an important role. The negative PPC is due to the fact that electrons in the well are photoexcited into the conduction band of the barrier layer. The return of the photoexcited electrons is prohibited by the band bending at interface. Because the band bending is small, the negative PPC thus occurs at low temperatures. On the other hand, at higher temperatures ($T>100\,\mathrm{K}$), positive PPC dominates the photoresponse, and it is caused by the spatial separation of photoexcited electrons and holes. This mechanism can also be used to explain the anomalous behavior of decay parameters as shown in Figs. 4 and 5. At low temperatures, the return of the photoexcited electrons from the barrier layer into the well layer reduces the decay rate of the electron concentration in the well and causes the increase of the decay time constant τ and also the reduction of the decay exponent β. At high temperatures, positive PPC becomes the dominant process, and thus β and τ behave like the decay parameters associated with the positive PPC effect observed in many other materials.[6,7] In this case, τ decreases and β increases with increasing temperature.

IV. CONCLUSION

We have presented detailed studies of the persistent photoconductivity effect in a two-side-doped $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum well, including pumping energy, temperature, and time dependencies. We have systematically measured the PPC decay parameters as functions of temperature in the entire PPC region. We observed the existence of the unusual negative photoconductivity effect in the low-temperature region $T<100\,\mathrm{K}$. We found conclusive results which show competition between the positive and negative persistent photoconductivity effects. At temperatures below a critical temperature $T_c(100\,\mathrm{K})$, the negative effect dominates, while above T_c the positive effect becomes the dominant factor. We suggest that a complete understanding of the decay and buildup kinetics in the entire temperature region must incorporate both the positive and negative effects. We conclude that the major positive effect is due to the band-to-band electron-hole generation in the well layer followed by the spatial charge separation and the negative effect is related to the pumping of the 2DEG electrons to the doped barrier layer.

This work was partially supported by the National Science Council, Republic of China.

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