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Observation of persistent photoconductivity in $Ga_xIn_{1-x}P/InP:Fe$ $(0 \leqslant x < 0.18)$

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Abstract. Persistent photoconductivity (PPC) has been observed in $Ga_xIn_{1-x}P/InP:Fe$ $(0 \leqslant x < 0.18)$ in a large temperature range from room temperature down to 77 K. The relationships between PPC and sample structure, material parameters, temperature and excitation time have been experimentally investigated. The results have been explained by the assumption that a macroscopic potential barrier between the film and the substrate separates the charge and thus delays recombination.

1. Introduction

There has been a considerable amount of experimental and theoretical effort directed towards the understanding of persistent photoconductivity (PPC) in some II-VI and III-V compounds and alloys [1-13]. Several mechanisms have been proposed for explaining the microscopic nature of PPC in the different materials showing this phenomenon. One of these models postulates that photoexcitation of electrons from deep-level traps, DX centres, which subsequently undergo a large lattice relaxation, is the origin of PPC. This idea has been applied to the explanation of PPC in AlGaAs and CdS [3-8]. Another model has proposed that PPC is due to the existence of a macroscopic potential barrier between the film and substrate which spatially separates the photogenerated electron–hole pairs, suppressing their recombination [9-12]. This model has also been used by Queisser and Theodorou to explain the kinetics of PPC in n-type GaAs grown on semi-insulating GaAs substrates and in GaAlAs/GaAs heterostructures [9, 10, 12]. PPC observed in semi-insulating bulk GaAs has also been explained by a theory involving a photosensitive state which is generated during the excitation [13].

GaInP ternary compound has attracted much attention, because of its application for wide-gap high efficiency LEDs and as a wide-gap emitter in a heterostructure bipolar transistor [14]. Much less attention has been paid to GaInP layers on InP substrates, primarily due to difficulties in growth arising from the lattice mismatch. Zn-doped GaInP/InP and undoped GaInP/InP:Fe have been successfully grown [15, 16], and the experimental results show that these materials can be used for high-speed Schottky photodetectors [15]. It is therefore of interest to study their photoconductivity behaviour.

In this paper, we report on the observation of PPC in $Ga_xIn_{1-x}P/InP:Fe$, where $0 \leqslant x < 0.18$, and on the relationships between PPC and temperature, sample structure, material parameters and excitation time.

2. Experimental details

The samples studied were grown by low-pressure metal-organic chemical vapour deposition (MOCVD). They consist of a semi-insulating substrate of InP doped with Fe, followed by a 1000 Å undoped InP buffer layer and finally by a nominally undoped (residually n-type) $Ga_xIn_{1-x}P$ film $(0 \leqslant x < 0.18)$. The compositions were determined by high resolution x-ray diffraction. The parameters of the samples studied are summarized in table 1.

The samples were cut in rectangular shapes. To make ohmic contacts, the samples were thoroughly degreased and chemically etched in a $H_2SO_4:H_2O_2$ (30%):H_2O (4:1:1) solution. Two Au-Ge (88:12)/Ni stripe contacts were evaporated onto each sample followed by a 10 s, 350 °C anneal in forming gas. Electrical current measurements were always performed in the linear part of the I-V characteristics in order to avoid nonlinear effects.

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Table 1. Characteristics of the studied samples.

Sample	CD1	CD2	CD3	CD4	CD5	CD6
Content of Ga (%)	0	1.65	2.8	3.7	11.72	17.09
Thickness of film (μm)	0.88	1.36	1.04	0.88	1.46	1.52

Optical excitation was provided by light from a tungsten lamp controlled by a KEPCO ATE38-8M current source, and passing through a grating monochromator. The samples were mounted in the cold finger of a liquid nitrogen cryostat. The excitation was homogeneous across the bulk of the sample in the full spectral range scanned in the photoconductivity measurements. A shutter was used as a means of switching on or off the excitation beam. The voltage drop across a resistor in series with the sample was measured by a programmable digital multimeter, and a computer was used to acquire data.

3. Results and discussions

Figure 1 shows a typical relaxation of photoconductivity for sample CD3 under the action of a light pulse generated by the shutter. The steady state was only reached after one day, and in some cases more than one day, after switching off the illumination. PPC has been observed for all samples listed in table 1.

Experimental results show that PPC is affected by both the sample structure and the material parameters. No persistent photoconductivity of the substrate was observed between 90 K and 294 K, but rather a sharp rise and decay, much smaller than 1 second. For the epitaxial layers, the lower the content of Ga, the longer is the photoconductivity decay, for a given temperature and light intensity. Figure 2 represents the PPC for samples CD1, 3 and 5 with differing Ga content. Sample CD1 has an epitaxial film of InP containing no gallium and shows the longest decay time.

Our experimental results also show that PPC is a function of temperature and excitation time. We have observed that the higher the temperature, the slower is the photoconductivity decay as shown for example in figure 3, and that the longer the excitation time, the slower is the decay.

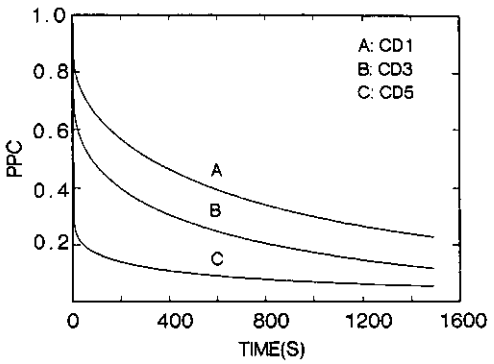

Figure 2. PPC decay curves for three representative samples: (A) CD1, (B) CD3, (C) CD5, at 294 K. Light wavelength is 7000 Å, and exposure time is 300 s.

We have fitted the PPC data at 85 K for sample CD2, using the following equation [12]

$$\Delta\sigma(t) \sim \Delta(nd)_t = ZL - \tfrac{1}{2}aZ \ln[1 + (t/\tau_0)] \qquad (1)$$

where n is the electron density and d is the width of the epitaxial layer; $\Delta(nd)_t$ is the excess sheet density of an electron as a function of time, which is the value of (nd) after illumination minus the original dark value, and is proportional to photoconductivity $\Delta\sigma(t)$; a is the electron Bohr radius, τ_0 is a carrier lifetime for vanishing spatial separation, Z is the volume density of hole-capturing traps in the substrate, and at $t = 0$, $ZL = \Delta(nd)_0$.

We have measured the Hall coefficient for sample CD2 at 85 K, and a value of $\Delta(nd)_0 = 1.291 \times 10^{11}$ cm^{-2} was obtained. Using the values of $a = 10^{-6}$ cm, $Z = 0.32888 \times 10^{16}$ cm^{-3}, $\tau_0 = 1.097 \times 10^{-9}$ s, a good fit to

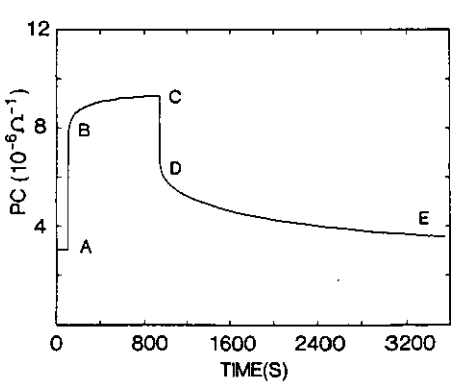

Figure 1. Relaxation of photoconductivity for sample CD3 at 294.4 K. The wavelength of exciting light is 6328 Å, and the exposure time (from A to C) is 15 min.

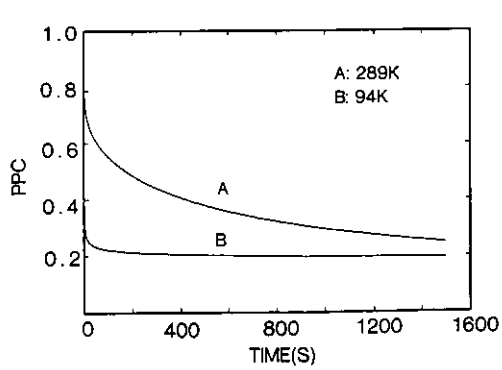

Figure 3. PPC decays obtained in sample CD4, for different temperatures. (A) 289 K; (B) 94 K. Light wavelength is 7000 Å and exposure time is 300 s.

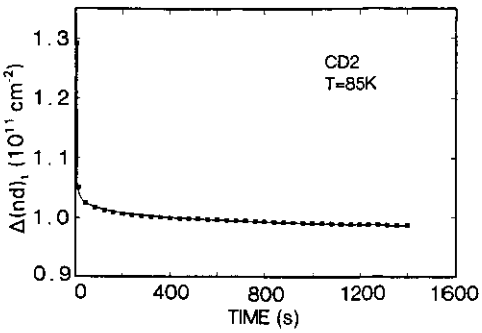

Figure 4. Persistent electron density $\Delta(nd)_t$ as a function of time for sample CD2 at a temperature $T = 85$ K. The full curve represents the calculated value from equation (1), with $Z = 0.32888 \times 10^{16}$ cm^{-3}, $a = 10^{-6}$ cm, $\tau_0 = 1.097 \times 10^{-9}$ s, $\Delta(nd)_0 = 1.291 \times 10^{11}$ cm^{-2}.

the experimental result has been obtained as shown in figure 4.

In figures 1–4, the excitation is above band gap. Each curve shown in figures 2 and 3 is normalized to unity at $t = 0$ and the dark current has been subtracted out.

In our samples low-resistance GaInP films (nominally undoped $n \sim 10^{15}$ cm^{-3}) are grown by MOCVD on high-resistivity compensated substrates ($n \leqslant 10^9$ cm^{-3}), with the thickness of the films being about 1 μm. It is clear that there are potential barriers in the n-n$^-$ junctions at the film-substrate interfaces, which can separate the charges and thus delay recombination causing PPC [12]. In our experiment, no decay was observed for the substrate, although spectral measurements of photoconductivity indicate the presence of deep levels in the Fe-doped InP substrate crystals, some of which have been associated in the past with anion and cation vacancies [17]. We have observed similar levels in the alloy films which move to higher energy with increasing gallium content; more details will be published elsewhere [18]. However, PPC has been observed only for epitaxial samples. In the large lattice relaxation model [3, 4], the recapture of electrons by DX centres is prevented by a thermal barrier at low temperatures. Our results, however, show that longer photoconductivity decays were observed at higher temperature. The photoconductivity decays follow a logarithmic dependence. These facts suggest the influence of the macroscopic potential barrier between the film and the substrate as the driving force for PPC.

According to this theory [12], PPC is determined by the recombination of electrons in the film with spatially removed trapped holes in the substrate. Therefore, the trapped hole distribution and concentration at time $t = 0$ after illumination directly affect the decay. The more trapped holes there are in the substrate, and the farther the trapped holes are from the film–substrate interface, the longer is the decay. Because the trapped hole distribution and concentration depend on the height of the potential barrier, diffusion rate and time, changes in any of these parameters will affect PPC. The band gap of $Ga_xIn_{1-x}P$ increases with the gallium content [16], and this is expected to lower the height of the potential barrier in the junction between the film and the substrate. Furthermore, increasing the gallium content is expected to reduce the diffusion constant, since the dislocation density increases with the gallium composition [16]. Therefore fewer trapped holes move into the substrate for given excitation conditions. This explains the faster decay which has been observed in figure 2.

The height of a potential barrier at the junction is an increasing function of temperature. Thus with a high barrier at higher temperature, relatively more holes move into the substrate, which gives rise to a slower decay as shown in figure 3.

We have used equation (1) to fit the PPC data at room temperature. For example, the curve A in figure 3 was fitted using a value of $\tau_0 = 9.8$ s, much larger than the carrier lifetime. This is because equation (1) is valid only at low temperature. In the theory [12] thermal excitation of holes out of traps and thermal surmounting of the barrier have been neglected. The potential barrier of the junction has a larger value at room temperature, which delays the recombination between the persisting electrons in the layer and the spatially removed trapped holes in the substrate. This is why so large a value of τ_0 was obtained.

A typical rise and decay curve such as the one shown in figure 1 also illustrates the effect of the macroscopic potential barriers. The light is turned on at A, and between A and B, the electrons and holes produced by light reach equilibrium in the carrier lifetime, so a sharp rise in photocurrent occurs. At the same time and since the film is thin, electrons and holes move to the edge of the space charge region, hole trapping occurs, and the potential barrier evolves continuously to a new equilibrium value. This needs a longer time and explains the slow rise observed between B and C. When the light is turned off at C, the current drops to D, because of the recombination of excess electrons and holes in the film, which appears as a fast decay. After D, the trapped holes move slowly into the film following thermal activation and recombine with electrons, giving rise to the very slow decay.

In summary, the above discussion shows that all of our experimental results can be explained by the presence of a macroscopic potential barrier between film and substrate.

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