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# Persistent photoconductivity in II-VI and III-V semiconductor alloys and a novel infrared detector

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Persistent photoconductivity (PPC) mechanisms, as well as the similarities and the differences of PPC properties in II-VI and III-V semiconductor alloys have been investigated. The potential applications based on PPC phenomenon in these two kinds of materials are discussed. We have observed that PPC induced in a II-VI mixed crystal by visible (above band gap) illumination can be quenched by long wavelength infrared radiation even at room temperature, which further supports our interpretation that PPC in II-VI mixed crystals is caused by random local potential fluctuations induced by compositional fluctuations. A newly developed infrared detector based on the PPC infrared quenching property of II-VI semiconductor alloys is also reported.

Persistent photoconductivity (PPC) phenomenon observed in a variety of semiconductors is currently under intensive investigation. Most studies on this subject have been concentrated on  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  ( $x > 0.22$ ) in which the defects ( $DX$  centers) are a well-known cause of strong PPC effect at temperatures  $T < 150$  K. Hence, PPC is very often taken as an evidence for atomic defect centers in semiconductors which supposedly have unusual properties.<sup>1</sup> Recently, a percolation transition has been observed in II-VI semiconductor alloys in the PPC mode, which suggests that the spatial separation between stored charge carriers by random local-potential fluctuations (RLPF) caused by compositional fluctuations is responsible for PPC observed in these materials.<sup>2-4</sup> In fact, previous work on impurity doped and compensated semiconductors has indicated that microscopic inhomogeneity caused by impurity distribution is the most likely reason for PPC phenomenon.<sup>5</sup> Full understanding of PPC is very important from the point of view of practical applications. The PPC effect can be utilized to optically vary the carrier concentration in a single semiconductor by simply varying excitation photon dose. Because most semiconductors exhibit the PPC effect only at low temperatures (150 K or below), device applications based on PPC phenomenon have not been previously established.

Because of different mechanisms for PPC observed in II-VI and III-V semiconductor alloys, the potential applications based on this phenomenon in these two kinds of materials could be very different. In this communication, we present PPC results for III-V and II-VI semiconductor alloys. We also report the results on a  $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{Se}$  II-VI mixed crystal in which PPC generated by visible (above band gap) illumination can be quenched very effectively by long wavelength (5–18  $\mu\text{m}$ ) infrared radiation even at room temperatures. Based on this PPC infrared quenching property, a novel infrared detector could be constructed. A number of advantageous features of this infrared detector will be discussed. The comparison between PPC properties

in II-VI and III-V semiconductor alloys will be concentrated on the following three aspects: PPC decay behavior, temperature region for existence of PPC, and the property of optical infrared quenching of PPC.

PPC decay behaviors have been investigated for these materials. In Figs. 1 and 2, we show representative PPC decay curves for  $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{Se}$  and  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , respectively. A similar behavior observed here is that PPC decay follows a stretched-exponential function at low temperatures ( $T < 90$  K for  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ <sup>6</sup> and  $70$  K  $< T < 220$  K for  $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{Se}$ ),  $I_{\text{PPC}}(t) = I_{\text{PPC}}(0)\exp[-(t/\tau)^\beta]$ , where  $\tau$  is the relaxation time constant and  $\beta$  the decay exponent. Although the PPC decay in both kinds of materials can be described by stretched-exponential functions, the decay parameters are very different. For II-VI semiconductors,  $\beta$  is around 0.8 and  $\tau$  is on the order of  $10^3$  s. For  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ ,  $\beta$  and  $\tau$  are on the order of 0.2 and  $10^{13}$  s, respectively, at low temperatures.

Furthermore, the Arrhenius plots,  $\ln \tau$  vs  $1/T$ , show two distinctive decay regions for both III-V and II-VI semiconductor alloys,<sup>7</sup> which is caused by different decay mechanisms involved in the high- and low-temperature regions. For  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  after excitation with certain photon dose,  $\tau$  has an activated temperature dependence in the region of  $T > 40$  K. This is because at  $T > 40$  K, the decay of PPC is caused by thermal activation of electron capture by  $DX$  centers and thus the slope of the Arrhenius plot in the region of  $T > 40$  K represents the electron capture energy by the  $DX$  centers. At low temperatures ( $T < 40$  K), the decay of PPC is caused by multiphonon tunneling capture in configurational space according to the large lattice relaxation (LLR) model,<sup>6,8,9</sup> or by wavefunction overlap in  $K$ -space between the electrons in the  $\Gamma$ -conduction band and impurities ( $DX$  centers) linked to the  $L$ -conduction band according to the  $L$ -conduction band effective-mass state model.<sup>10,11</sup> For II-VI semiconductor alloys, the PPC decay is caused by wavefunction overlap between electrons and holes in real space at low temperatures and by electron

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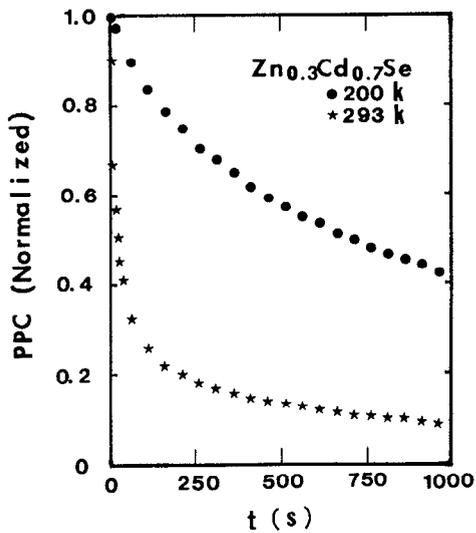


FIG. 1. Decay of PPC in  $Zn_{0.3}Cd_{0.7}Se$  at 200 K (●●●) and 293 K (\*\*\*). The dark current has been subtracted out. Each curve is normalized to unity at  $t = 0$ , the moment excitation light is removed.

thermal activation from the local potential minima to maxima to recombine with holes at high temperatures; therefore, the thermal barrier approximated from the high-temperature region corresponds to the average energy difference between the local potential minima and maxima.

In Fig. 3, we show a schematic of the real space potential profile at the conduction and the valence band edges of a II-VI mixed crystal. Because of compositional fluctuations, photoexcited electrons (holes) are stored in low potential sites in the conduction (valence) band. Spatially, the low potential sites in the conduction band are separated from those in the valence band leading to very long carrier lifetimes. Consequently, the electron-hole recombination barrier  $E_{rec}$  depends uniquely on the degree of the fluctu-

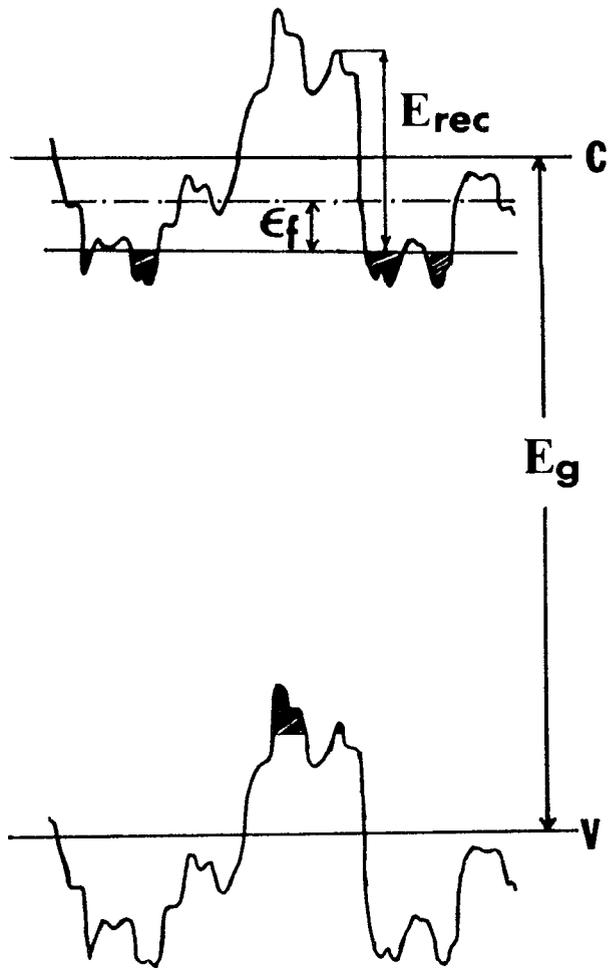


FIG. 3. Schematic of the real space energy diagram at the conduction and the valence band edges ( $k = 0$ ); it represents a profile of random local-potential fluctuations caused by compositional fluctuations in a II-VI mixed semiconductor. The meandering lines show band bending. The solid lines labeled C and V indicate, respectively, the positions of the conduction band and the valence band edges in the absence of the random local-potential fluctuations. The lower solid line in the conduction band shows the electron quasi-Fermi level, the dashed-dotted line shows the electron percolation level. Photoexcited electrons and holes are stored in shaded regions (after Ref. 5).

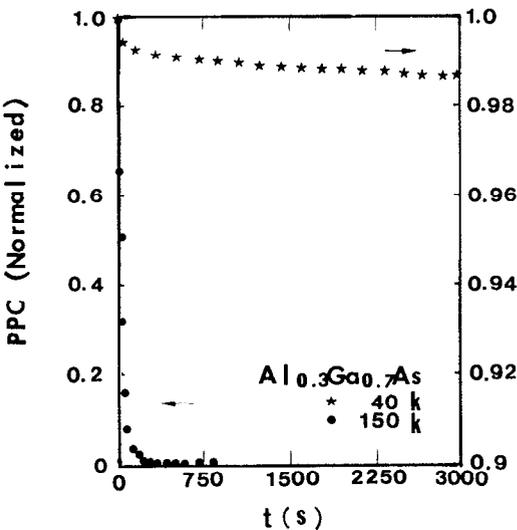


FIG. 2. Decay of PPC in  $Al_{0.3}Ga_{0.7}As$  at 40 K (\*\*\*), and 150 K (●●●).

ation of the sample, which is about 100 meV for  $Zn_{0.3}Cd_{0.7}Se$  and is only about a few meV for a higher quality (lower degree of compositional fluctuations)  $CdS_{0.5}Se_{0.5}$  sample.<sup>7</sup>

Furthermore, in  $Zn_{0.3}Cd_{0.7}Se$ , below a certain temperature,  $T < 70$  K, the electrons are highly localized and the charge transport becomes negligible and no PPC effect can be observed. As temperature increases, the conductivity is induced either by electron thermal activation hopping between localized sites ( $T < T_C$ ) or by electrons percolating through the network of accessible sites ( $T > T_C$ ), where  $T_C$  is a critical temperature at which electrons experience a phase transition from hopping to percolation conduction states.<sup>2-4</sup> As temperature increases to an upper limit value, PPC thermally quenches instantaneously. Therefore, there exists an upper temperature limit  $T_U$  and a lower temper-

ature limit  $T_L$  for the observation of PPC in II-VI mixed crystals. The PPC temperature range as well as  $T_C$  are uniquely determined by the degree of the sample compositional fluctuations. Experimentally,  $T_C$ ,  $T_U$ , and  $T_L$  found for  $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{Se}$  are about 120, 300, and 70 K, respectively. For the higher quality  $\text{CdS}_{0.5}\text{Se}_{0.5}$  sample,  $T_C$  and  $T_U$  are about 15 and 150 K, respectively, and PPC is observable down to 8 K.  $T_L$  for  $\text{CdS}_{0.5}\text{Se}_{0.5}$  has not yet been determined because our current low-temperature system can achieve a lowest temperature of about 8.5 K. For  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , there is no lower temperature limit for PPC. Even at temperature  $T = 0$ , photogenerated electrons still have velocities varying from 0 to Fermi velocity  $v_F$  due to the Fermi distribution of electrons in the conduction band. Thus PPC is observed in the entire temperature region of  $T < 150$  K. An important fact we would like to indicate here is that from the RLPF model, in II-VI semiconductor alloys, the temperature region for PPC and  $E_{\text{rec}}$  can be controlled by varying the degree of fluctuation in the sample, and so one may obtain strong PPC effect at room temperatures. In contrast, the upper limit temperature for PPC in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  depends on the electron capture barrier, which is predetermined by the atomic configuration of the DX center, and cannot be changed easily. This is why no PPC can be observed at  $T > 150$  K in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , so practical applications based on the PPC phenomenon in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  may be limited.

A unique property for PPC in II-VI semiconductor alloys is expected—infrared PPC quenching. As indicated in Fig. 3, once charge carriers are stored in potential minima, by illumination with infrared photons whose energy is on the order of  $E_{\text{rec}}$ , electrons can be transferred to the maximum of the potential height to radiatively recombine with holes, which will result in a quenching of PPC and a stimulation of luminescent emission of photons with energy on the order of  $E_g$ . Experimentally, we indeed observe in  $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{Se}$  that PPC generated by visible illumination can be optically quenched by infrared radiation. Figure 4 shows experimentally obtained kinetics of the PPC infrared quenching at room temperature. We see that the quenching is evident. Limited by the time response of the detection instrument (digital electrometer), the quenching time shown here is instantaneous. The amplitude of PPC quenching depends on the intensity of the infrared radiation. Experimental observation of infrared quenching of PPC further supports our RLPF model for PPC in II-VI semiconductor alloys. It is well known from earlier work that PPC induced in  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  cannot be optically quenched,<sup>1,12</sup> which has also been further experimentally proved recently.<sup>13</sup>

The infrared PPC quenching property makes II-VI mixed crystals a novel room-temperature infrared detector with a number of advantages, including (a) high speed: infrared quenching is a very fast process because infrared

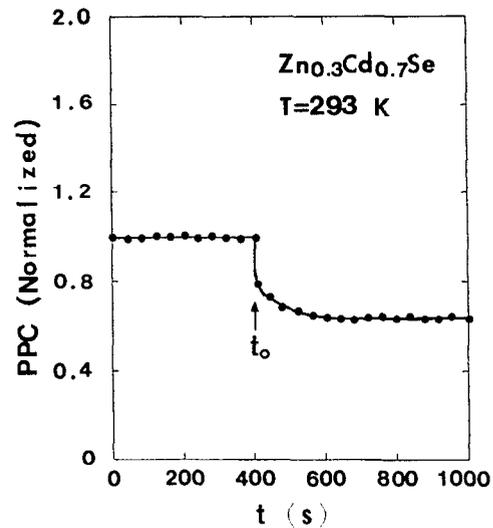


FIG. 4. Experimentally observed kinetics of infrared quenching of PPC in a  $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{Se}$  mixed crystal at room temperature. This is obtained by building-up PPC with visible (room) light to a saturation level, and then at  $t_0$  exciting the crystal with a broad band infrared source ( $5\text{--}18\ \mu\text{m}$ ) while maintaining visible illumination during the course of measurement.

excitation and free carrier recombination processes in these materials occur on a sub-nanosecond scale, (b) wider spectral response region: since  $E_{\text{rec}}$  can be varied, detectors with different spectral response regions, from a few  $\mu\text{m}$  to about  $30\ \mu\text{m}$ , can be fabricated from II-VI mixed crystals for different application purposes. A room temperature, long wavelength infrared detector is very important in many cases, (c) low cost: the fabrication method of this type of infrared detector is simple and so the cost will be low. Detailed parameters, such as operating spectral region, temperature, and speed of the infrared detector will be investigated further.

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