High-pressure study of photoluminescence in indium phosphide at low temperature

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Photoluminescence measurements on n-type InP have been carried out under hydrostatic pressure in a diamond anvil cell at 20 K. The photoluminescence peak corresponding to the direct-band-gap transition has been observed up to 12 GPa and has been found to change sublinearly with pressure, similar to room-temperature measurements. The effect of shear strains on the photoluminescence signal is also discussed. The intensity of the luminescence signal was obtained as a function of pressure.

INTRODUCTION

The effect of pressure on the electronic structure of InP has been investigated at room temperature by previous studies of optical absorption,[1] photoluminescence (PL) (Refs. 1–3) and Hall measurements.[4] Hall measurements[4] were interpreted in terms of a linear dependence on pressure of the direct gap E_0 while PL and absorption measurements[1–3] indicated a sublinear behavior. The intensity of the PL signal was observed to decrease exponentially at pressures above 9 GPa (Ref. 1) and 7 GPa (Ref. 2), respectively. This change was attributed to the crossing of the Γ and X conduction-band minima. The critical pressure for the inversion of the two conduction-band minima has been predicted by Kobayashi *et al.*[2] to be 8 GPa, while Müller *et al.*[1] calculated this pressure to be 10.4 GPa. Hall measurements[4] indicated that this crossing is complete at 7.5 GPa.

The purpose of the present work was to extend PL measurements at high pressure to low temperature (20 K). The first reason for this is that PL signals are intensified and narrowed at low temperature, so that the variation of $E_0(P)$ can be measured with greater precision. Second, it was hoped that weaker signals from the X_{1C}-Γ_{15V} transition could be detected, so that the Γ_{1C}-X_{1C} crossing could be inferred directly from the measurements.

EXPERIMENTS

An n-type InP ($n=7.3\times10^{16}$ cm^{-3}) sample, 40 μm thick, was loaded in a gasketed diamond-anvil cell (DAC) together with a small ruby chip. The volume of the sample was approximately ten times smaller than the hole in the gasket. At low temperature argon was employed as the pressure transmitting medium to avoid shear strains. The technique of loading Ar in the DAC has been described previously.[5]

The PL was excited with the 514-nm line of a cw Ar ion laser. The laser power measured at the cryostat window was maintained at 27 mW, although at higher pressure, where the signal became very weak, the laser power was increased by a factor of 20. Local heating produced a change of 0.5% in the position of the PL peak. The PL signal was analyzed with a 1-m SPEX double plus a third monochromator and detected with an RCA 31034 photomultiplier tube in the photon-counting mode. The pressure was measured by the ruby fluorescence technique.[6] The temperature correction for the ruby fluorescence was unnecessary since the ruby signal was measured simultaneously with the signal from the sapphire window in contact with the diamond. The experiment was carried out at 20 K, with the temperature in the gasket region measured with a germanium resistance thermometer.

RESULTS AND DISCUSSION

The PL spectrum was dominated by a single peak due to the band-to-band transition at the lowest energy gap E_0. Figure 1 shows the shift in the PL peak E_m with pressure. It is assumed that E_0 varies with pressure in the same way as E_m. The fitting of the data with a quadratic equation of the form

$$E_m = E_m(0) + aP + bP^2$$

gives

$$E_m(0) = 1.393 \pm 0.005 \text{ eV} ,$$

$$a = 0.075 \pm 0.002 \text{ eV/GPa} ,$$

$$b = -0.0012 \pm 0.0005 \text{ eV/GPa}^2 .$$

The variation of E_m with pressure at 20 K was found to be similar to the behavior reported at room temperature.[1–3] This contrasts with the behavior of GaAs which

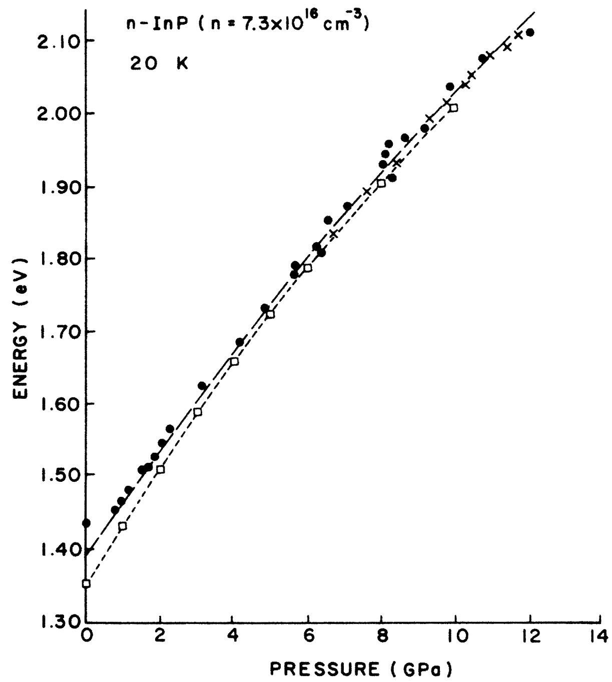

FIG. 1. Variation of the PL peak with pressure. ●: up in pressure; ×: down in pressure; ——: computer fit; □: room-temperature data from Ref. 1.

was shown to have a linear dependence on pressure at low temperature,[7–9] but a sublinear variation at room temperature.[10] The difference in the low temperature behavior for GaAs cannot be ascribed to nonhydrostatic stresses because different workers used different media and procedures in their work.

In one of the runs the argon did not fill the gasket hole completely, causing the gasket to partially collapse and compress the sample. Measurements were conducted in this case to determine the effect of nonhydrostatic stresses on the PL signal. In the presence of shear strains, the PL signal became broader [full-width at half-maximum (FWHM) = 50 meV] and resulted in the appearance of two peaks (Fig. 2). This is probably due to the splitting of the valence band under nonhydrostatic pressure as predicted by Tsay and Bendow.[11]

The intensity of the PL signal decreased when the pressure was increased above 6.5 GPa. At 12 GPa the signal was 3 orders of magnitude smaller than at low pressures (see Fig. 3). This decrease in intensity has been attributed by Müller *et al.*[1] and Kobayashi *et al.*[2,3] to the crossing of the Γ and X conduction-band minima. From intensity behavior both works inferred the pressure at which this crossing occurred. In the present work, numerous runs on InP resulted in only a single peak observed up to the maximum pressure. This peak was assigned to the direct transition Γ_{1C}-Γ_{15V}. There were no attempts to fit the intensity data, since the intensity varied between runs (Fig. 3), and small changes in sample orientation caused large changes in the intensity.

There were other peaks observed that differed from the main peak by 40 meV. These peaks were associated with

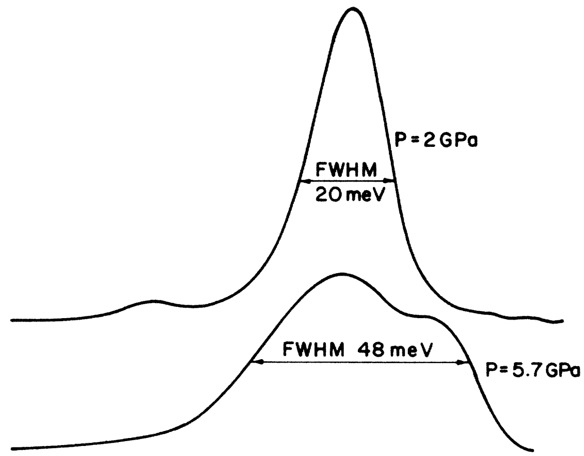

FIG. 2. Typical luminescence spectra. (a) Hydrostatic conditions, (b) nonhydrostatic conditions.

impurity levels. Their variation with pressure followed the same behavior of the main PL peak. The average FWHM of the PL signal was 23 meV. A PL peak due to the transition X_{1C}-Γ_{15V} was not observed. However, this transition cannot be ruled out because of the poor signal-to-noise ratio of the spectra at high pressure. It is also possible that at 20 K, and 12 GPa, complete crossover was not achieved. The decrease in intensity observed at 6.5 GPa can be explained by the transferring of electrons to the X minimum.

The PL signal disappeared for presures above 12 GPa, an indication of the transition to the metallic phase.[12,13] This is the first time that PL has been observed in InP up

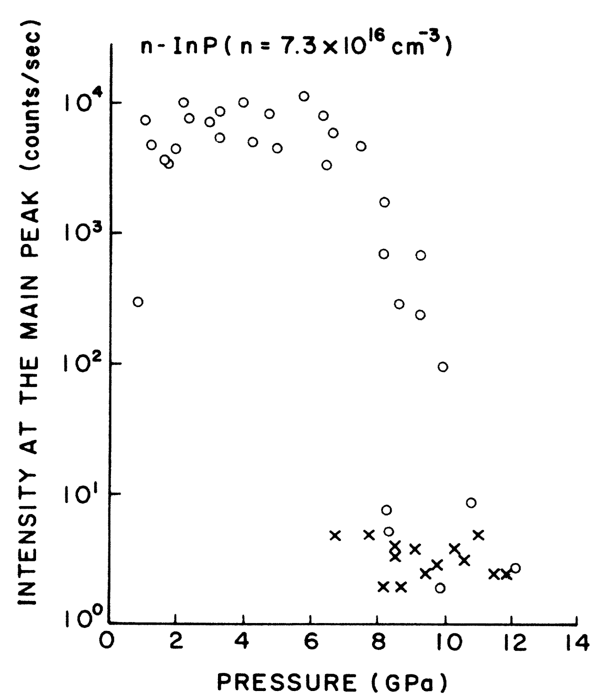

FIG. 3. Change of the maximum intensity of the PL peak with pressure. ○: up stroke; ×: down stroke.

to 12 GPa. When the pressure was decreased, the intensity of the signal remained very weak. This could be caused by (1) hysteresis in the semiconductor-to-metal transition, (2) formation of a new phase on release of pressure, as in Ge (Refs. 14 and 15) or Si (Refs. 15 and 16), or (3) scattering of the PL signal by grain boundaries and dislocations formed by the phase transitions.

Summarizing, we have found that in *n*-type InP, having a concentration of 7.3×10^{16} cm^{-3}, there is only one transition observed, Γ_{1C}-Γ_{15V} up to 12 GPa at 20 K. The PL peak changes sublinearly with pressure, in agreement with room-temperature measurements.

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