Photogalvanomagnetic effect in structures based on a semiconductor with a symmetry center

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(Submitted 11 January 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **61**, No. 4, 290–293 (25 February 1995)

A photovoltaic signal has been observed to arise in structures with asymmetric quantum wells based on the narrow-gap semiconductor $Pb_{1-x}Sn_xSe$ in a magnetic field at $T=4.2$ K. The effect is attributed to a photovoltaic effect induced by a magnetic field in structures with asymmetric quantum wells based on a semiconductor with a symmetry center.© *1995 American Institute of Physics.*

The photovoltaic effect occupies a special place among the many photoelectric effects. The reason is that the direction of the current which arises in this effect is determined not by external forces (an electric field; a gradient of the temperature, the concentration, or the light intensity; etc.) but by the symmetry properties of the crystal. This effect can be observed in any crystal lacking a symmetry center, including ferroelectrics and piezoelectrics.[1] The magnitude of the photovoltaic effect may be tens of times the width of the band gap of the semiconductor.

The existence of a photovoltaic effect in a structure with an asymmetric quantum well or in structures with coupled quantum wells of different widths in a magnetic field was predicted theoretically in Ref. 2. The effect is associated with a lifting of degeneracy for carriers for which the centers of the cyclotron orbits have different coordinates (carriers which are moving near potential barriers with different characteristics, e.g., different shapes or heights, become different). Calculations have shown that, if the distribution function is not the equilibrium function, currents arise in the structures, in the direction determined by the vector product $\mathbf{L}\times\mathbf{H}$, where $\mathbf{L}$ is the normal to the epitaxial structure, and $\mathbf{H}$ is the magnetic field. This effect should occur in structures based either on crystals which lack a symmetry center or on crystals which have one. A photovoltaic effect induced by a magnetic field was observed in Ref. 3 in $GaAs/Ga_{1-x}Al_xAs$-based structures with asymmetric quantum wells. In GaAs, however, there is also a bulk photovoltaic effect, associated with the absence of a symmetry center. It is thus worthwhile to measure the photovoltaic effect in structures based on a semiconductor which has a symmetry center.

In this letter we are reporting observation of a photovoltaic effect in a magnetic field in structures with asymmetric quantum wells based on narrow-gap semiconductors with the general formula $PbSe/Pb_{1-x}Sn_xSe$, in which there is no bulk photovoltaic effect.

Epitaxial $PbSe/Pb_{1-x}Sn_xSe$ ($x\sim0.06$) structures, both p- and n-type, were grown by molecular beam epitaxy on insulating $(111)BaF_2$ substrates on an ÉP-1201 apparatus. The carrier concentrations and mobilities at 77 K were typically 3×10^{17} cm^{-3} and 1×10^4 cm^2/(V·s). The composition (x) of the quantum wells was found from photoluminescence spectra for structures with a well width >400 Å. The structures contained up to seven pairs of layers. The widths of the quantum wells and the potential barriers were

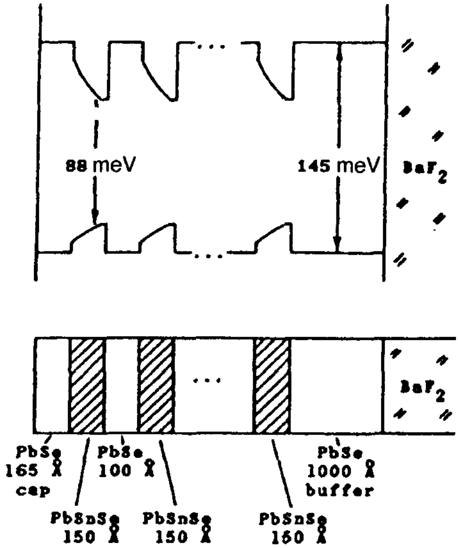

FIG. 1. Composition of the p-$Pb_{1-x}Sn_x$ $Se/PbSe/BaF_2$ ($x \simeq 0.06$) structure with asymmetric quantum wells, along with a simplified corresponding energy-band diagram. There are seven wells.

varied over the range 50–400 Å. The potential well was approximately a rectangular trapezoid with an inclined edge toward the exposed surface of the structure. The band discontinuity at the heterojunction has not been studied thoroughly for the $PbSe/Pb_{1-x}Sn_xSe$ heterojunction; we adopted a ratio $\Delta E_c/\Delta E_v=2$. Figure 1 shows the composition of one of the structures along with a simplified corresponding energy-band diagram, which ignores stress. The structure as a whole does not have a symmetry center. Samples with dimensions of 1×5 mm were cleaved out. Contacts were applied to all the epitaxial layers at the ends of the structure and shielded.

The photoconductivity and the photovoltaic effect were measured at temperatures of 4.2 and 77 K in the geometry shown in the inset in Fig. 2. A magnetic field of 0–10 kG was directed along the plane of the structure. The exciting light arrived along the perpendicular to the plane of the quantum wells. The photosignal was measured in a direction perpendicular to the magnetic field. The exciting light was the beam from a CO_2 laser ($h\nu = 117$ meV) or a He–Ne laser ($h\nu = 1.97$ eV), modulated in either case at a frequency of 600 Hz. The excitation power was varied up to 10 W/cm^2. The photon energy of the CO_2 laser beam was sufficient to excite only the narrow-gap component of the superlattice, E_g(PbSnSe)$=88$ meV; it was not sufficient to excite the wide-gap component, E_g(PbSe)$=145$ meV. This excitation method is preferable, since the relatively weak absorption at this wavelength ($\alpha \sim 10^2$ cm^{-1}) leads to an excitation of the sample which is uniform over depth.

The signal was displayed directly on an oscilloscope after amplification by a wideband amplifier or a phase-sensitive nanovoltmeter. The photoconductivity and the photovoltaic effect observed in the structure each had a relaxation time shorter than 10 μs. (The increase in the photoconductivity relaxation time at low excitation levels which was observed in Ref. 4 was inconsequential in the present case, because of the high excitation level.)

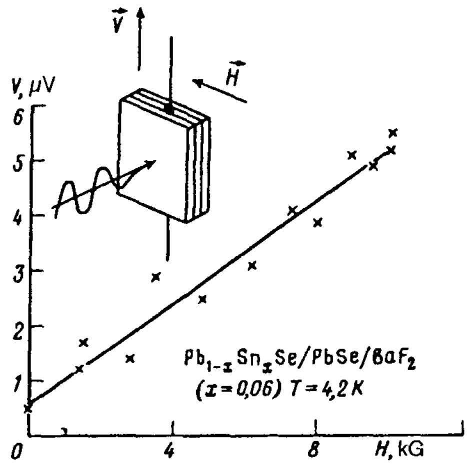

FIG. 2. Photovoltaic signal versus the magnetic field for the structure in Fig. 1. The effect was excited by a CO_2 laser beam with a photon energy $h\nu = 117$ meV satisfying E_g(PbSnSe) $< h\nu < E_g$(PbSe).

We observed a photovoltaic signal induced by the magnetic field in the direction perpendicular to **H** and **L**. The magnitude of this signal is shown as a function of the magnetic field in Fig. 2 for the case in which a p-$Pb_{1-x}Sn_xSe/PbSe/BaF_2$ ($x \simeq 0.06$) structure (shown in Fig. 1) is excited by a CO_2 laser beam at $T = 4.2$ K. The width of the quantum well here is ~ 150 Å . The signal becomes completely independent of the magnetic field at $T = 77$ K. When the magnetic field is reversed, the polarity of the signal changes. To identify the component of the signal which was the ordinary photoelectromagnetic effect (the Kikoin–Noskov effect), we also excited the sample from the substrate side, without changing the direction of the magnetic field. The sign of the signal did not change as a result, indicating that the ordinary photoelectromagnetic effect makes only a small contribution to the signal. This is a natural result, since the linear photoelectromagnetic effect is observed only when the absorption is highly nonuniform over thickness, while the quadratic photoelectromagnetic effect, due to different recombination rates at the surfaces of the structure, is small in magnitude. The apparent reason for the small photovoltaic signal at $H = 0$ is a longitudinal nonuniformity of the sample; its magnitude did not affect the magnetic-field dependence of the photovoltaic signal. Since the signal amplitude was quite small, we checked for effects of stray pickup from the electromagnet and the laser on the signal. These effects turned out to be negligible. In measurements of the photovoltaic signal along the magnetic field, the magnitude of the signal was lower by more than an order of magnitude. The effect of the magnetic field on the photovoltaic signal disappeared at a quantum-well width greater than 360 Å.

We also observed a weak dependence of the photovoltaic signal on the magnetic field at $T = 4.2$ K on epitaxial layers of p-PbSe with thicknesses less than 0.5 μm, with $p(77) \sim 4 \times 10^{17}$ cm^{-3} and $\mu(77) \sim 7 \times 10^3$ cm^2/(V·s), with excitation by the He–Ne laser. The effect was observed in a very small fraction of the samples tested, and it was weaker than the effect in structures with quantum wells under otherwise equal conditions.

We attribute the observed dependence of the magnitude of the photovoltaic signal on the magnetic field to a photovoltaic effect induced by the magnetic field in an asymmetric structure based on a semiconductor which has a symmetry center (although the structure as a whole does not have a symmetry center). In structures with an asymmetric wave function (a consequence of the asymmetry of the quantum well in the case at hand), the wave vector corresponding to the minimum of the dispersion curve $E(\mathbf{k})$ is shifted by a magnetic field which lies in the plane of the epitaxial layer. The shift is in the direction perpendicular to the magnetic field. The symmetry under time reversal, $E(\mathbf{k}) \neq E(-\mathbf{k})$, is thus broken. The magnitude and sign of the shift depend on the particular wave function; they are different for different quantum-well levels. At thermodynamic equilibrium, an averaging of the carrier flux over the magnitude of the wave vector leads to a zero current, which is a manifestation of the second law of thermodynamics. In the case of a nonequilibrium distribution function, the current acquires a nonzero component, which lies in the plane of the potential well and which is perpendicular to the magnetic field. The exciting photon from the CO_2 laser has enough energy to excite only the narrow-gap component, so carriers are excited in the quantum wells only to quantum-well levels in the conduction band. A relatively high pump power causes the distribution function to deviate from equilibrium. As the temperature is raised to 77 K, the smearing of the quantum-well levels and intersubband transitions suppress the effect. Unfortunately, we do not know the properties of the quantum well accurately enough to carry out a quantitative calculation of the magnitude and sign of the effect.

The optimum quantum well for observation of a magnetic-field-induced photovoltaic effect is an asymmetric well with one or two quantum-well levels. If there are numerous levels, their contributions to the effect may cancel out. For example, we were unable to observe the effect in structures with a well width >360 Å , in which there are three or more quantum-well levels. The magnetic field has its strongest effect on the photovoltaic signal at a well width ~ 150 Å , at which the second quantum-well level arises.

The apparent reason why the magnetic field has only a weak effect on the photovoltaic signal for certain epitaxial p-PbSe/BaF_2 layers is a band curvature near the surface, which arises because of a trapping of carriers in surface states.[4] Because of the large width of the well formed in the process (300–1000 Å), the number of quantum-well levels becomes large, so the effect becomes weak.

In summary, we have observed, for the first time, a photovoltaic effect induced by a magnetic field in quantum-well structures based on a semiconductor having a symmetry center. The photogalvanomagnetic effect observed here is weak; the primary reason for this weakness is apparently the relatively high carrier concentration, which makes the resistivity of the sample low.

We wish to thank M. V. Valeĭko and B. N. Matsonashvili for assistance in this study. This study had financial support from the Russian Fund for Fundamental Research (Project 94-02-05849-a).

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Translated by D. Parsons