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Magnetic Quantum Oscillations in the Auger Transition Rate

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The first observation of magnetic quantum effects in Auger recombination is reported. Experiments were carried out with the semiconducting compounds $Hg_{1-x}Cd_xTe$. In addition to significant oscillations, the lifetime increases strongly with the magnetic field, as a result of the magnetic-field–induced spin polarization. The effect provides a very sensitive method for the determination of band parameters and may give valuable information on the electron-electron interaction in magnetic fields.

In some small-band-gap semiconductors even at low carrier densities, the recombination of nonequilibrium carriers is governed by the Auger or impact recombination process. This recombination process is due to the electron-electron interaction between the free carriers. The Auger effect may be considered as a two-electron collision in which the energy lost by one electron in the recombination transition is taken up by a second electron.[1] The situation is sketched in Fig. 1 for the case of an electron-electron collision. Because of the conservation of both the energy and the momentum, the transition does not proceed vertically in the energy-momentum representation of the bands. However, the situation becomes quite different in quantizing magnetic fields, in which case the bands are shifted and split into Landau levels as shown in the figure.

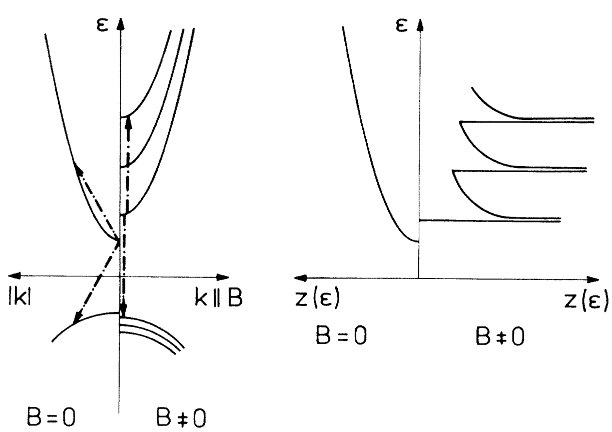

FIG. 1. Auger recombination and density of states with and without magnetic field for a semiconductor with a simple band structure.

Thus at any given magnetic field a vertical transition is possible; and because of the modulation of the density of states in quantizing magnetic fields, oscillations in the Auger transition rate might occur in such magnetic fields. We are reporting the first experimental evidence of this magnetic quantum effect, observed for various compositions of the $Hg_{1-x}Cd_xTe$ alloy. Theoretical studies of this interesting feature have recently been done by Takeshima[2] for InSb, but his calculations do not consider either the strong nonparabolicity usually found in small-gap semiconductors or the effect of spin polarization in a quantizing magnetic field.

The experiments were carried out for various compositions of the semiconducting $Hg_{1-x}Cd_xTe$ alloy ($0.165 \leq x \leq 0.216$, with an extrinsic electron density between 10^{14} and 10^{15} cm^{-3} at 4.2 K). This small-band-gap semiconductor has recently been demonstrated to display the largest known Auger recombination cross section.[3-5] The lifetime of the photoionized carriers was determined from the time-resolved transient carrier decay. The experimental method has been published elsewhere[4] but it is modified by the additional application of a magnetic field. The predominance of the Auger recombination process in the experiment was deduced from the variation of lifetime with the excess carrier density, which characterizes reliably the domant recombination mechanism.[4]

Experiments were performed at a temperature of 4.2 K and in magnetic fields up to 8 T. As shown in Fig. 2, a pronounced modulation of the lifetime was observed. All investigated samples exhibit a strong increase of lifetime at small magnetic fields. The lifetime increases approxi-

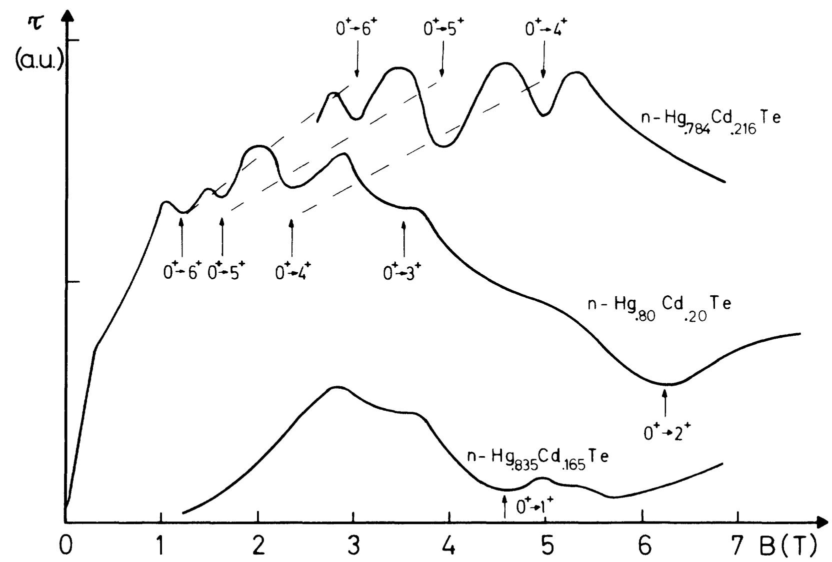

FIG. 2. Carrier lifetime versus the magnetic field, as deduced from photoconductivity experiments. The lifetime maximum of sample $Hg_{0.80}Cd_{0.20}Te$ corresponds approximately to 100 μsec.

mately by a factor of 20 in this region. At higher fields a significant oscillatory behavior is to be seen. The modulation seems to depend on the composition of the samples. The composition with the narrowest band gap ($x = 0.165$, $\mathcal{E}_g = 14$ meV) exhibits the least oscillations in the range of magnetic fields under study.

Two main experimental results have been found, as demonstrated in Fig. 2. (1) The lifetime shows pronounced oscillations with the magnetic field, depending on the composition of the $Hg_{1-x}Cd_xTe$ crystals; and (2) the lifetime increases strongly with magnetic field at small fields.

The calculations of Takeshima were carried out, neglecting the strong nonparabolicity of the conduction band. For the experimental proof of the oscillations a more accurate knowledge of their field dependence is necessary. Therefore we have recalculated the lifetime minima as a function of the magnetic field, taking into account both the nonparabolicity of the conduction band and the spin splitting of the Landau levels. The valence band edge was assumed to be constant since the ratio of conduction band to valence band effective mass is about 0.03 for InSb. The data were treated according to the relation given by Lax *et al.*[6] A comparison of Fig. 3 with Fig. 4 shows that because of the nonparabolicity, the minimum corresponding to a transition $0 \to 3$ is expected at a rather high field of 32 T instead of 12 T.

Figure 5 shows our calculations for the semiconducting $Hg_{1-x}Cd_xTe$ alloy. Calculations have been made for compositions with a band gap between 0 and 120 meV, corresponding to $0.156 \leq x \leq 0.23$. In this figure the magnetic field B_R corresponding to the lifetime minima is plotted as a function of the composition for the transitions 0^+

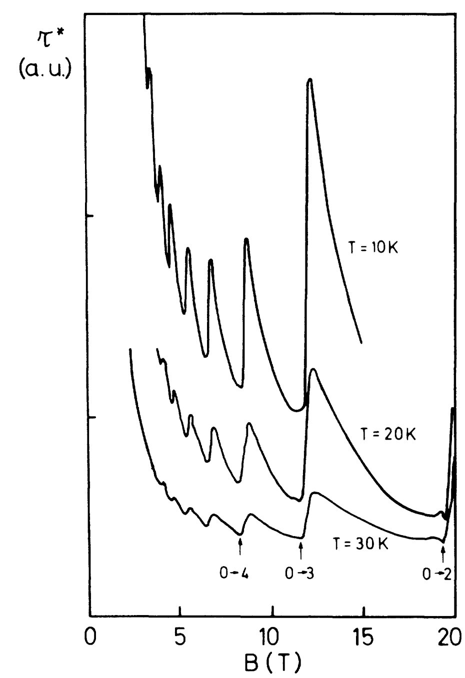

FIG. 3. Numerical data of the Auger lifetime versus the magnetic field (Ref. 2). (InSb, parabolic conduction band.)

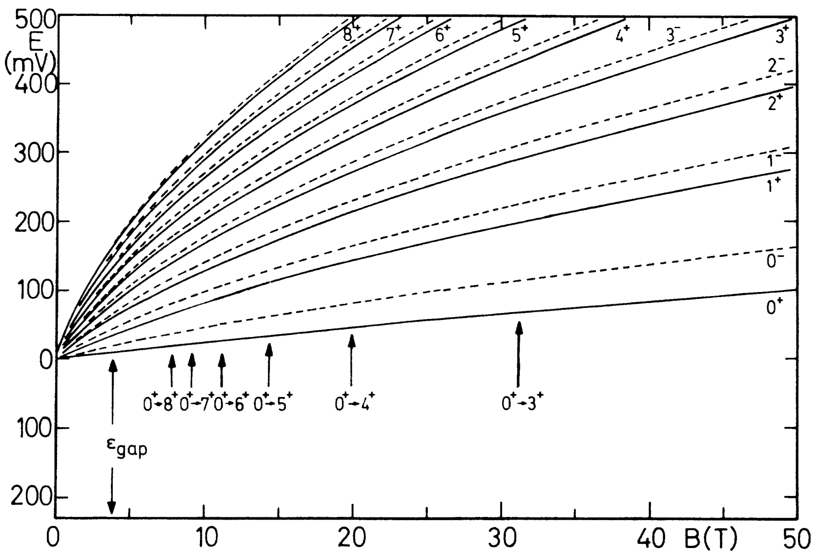

FIG. 4. Energy of the conduction-band Landau levels $0\mp, \cdots, 8\mp$ versus the magnetic field in InSb. The arrows mark possible vertical Auger transitions, with the nonparabolicity of the conduction band taken into account.

$\to 1^+$ to $0^+ \to 7^+$. The calculations were performed with the strong nonparabolicity of the conduction band in the alloy taken into account and with band parameters deduced from various experiments.[7] The smaller band gap and the smaller effective mass in this material cause a shift of the oscillations to magnetic fields smaller by one order of magnitude in comparison with InSb.

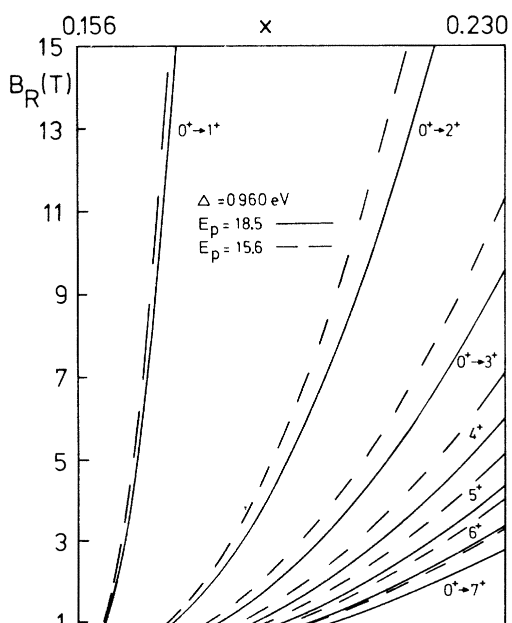

FIG. 5. Magnetic field of Auger lifetime minima versus the concentration x or corresponding band gap for n-$Hg_{1-x}Cd_xTe$.

From the dependence of the oscillation minima on both the magnetic field and the composition of the samples we conclude that the observed data represent the first evidence of the oscillations predicted by Takeshima.[2] The agreement between the experimental results and our calculations as shown in Fig. 5 is satisfactory. One has to consider the accuracy of the band parameter of the $Hg_{1-x}Cd_xTe$ alloy and the precision in the determination of the composition ratio x. For instance, a small deviation of only 1% of the x value might shift the position of the low-order minima anywhere between 10 and 100% on the magnetic field scale. With this in mind, we conclude that the smeared structures found with the $Hg_{0.835}Cd_{0.165}Te$ sample are caused by a slightly inhomogeneous composition. Inspection of Fig. 5 shows that for this sample, minima of higher order than $0^+ \to 1^+$ are expected below 0.5 T. The samples with higher composition ratios show a number of oscillations which allow identification of the various minima. So we think that this new quantum effect can provide a very sensitive method for the determination of either the band parameters or the concentrations x.

The measured amplitudes do not show the strong increase with decreasing transition order as calculated by Takeshima (see Fig. 3). This discrepancy might be due either to the specific interpretation of the given experimental data or to the theoretical model assumed. For instance, the experimental results might be influenced by a second recombination mechanism as a radiative recombination. Such a competing process could yield a damping of the oscillations. Neither damping—in other quantum effects described by the Dingle temperature—nor a field-dependent screening of the Coulomb potential has been considered in the calculations. Thus a more refined theory and a more detailed comparison with the experiment might give valuable information on the Coulomb interaction in high magnetic fields.

It has been observed for all samples at small fields that the lifetime increases by more than one order of magnitude, contrary to the calculations. A magnetic freezeout of carriers would result in an increase of lifetime as expected by theory. However, measurements of the Hall effect with the same samples yield a carrier density constant over the investigated range of magnetic fields. We believe the increase of lifetime to be mainly due to the spin polarization taking place at fields up to the quantum limit. The quantum limit was observed with all samples between 0.3 and 0.6 T. At higher fields all electrons are in the lowest Landau level 0^+, having like spins. Takeshima did not consider this effect in his calculations; he even assumed both collisions of electrons with opposite spins and of electrons with like spins to have the same transition probability. Thus taking into account the spin polarization of the electrons, we would double the lifetime expected in the Takeshima calculations. This will serve to describe qualitatively the experimental data; an improved calculation including the effects of the interaction between carriers with like spins may even yield quantitative agreement.

In conclusion, we have presented experimental evidence for magnetic quantum oscillations in the Auger effect and its strong variation with magnetic field. Because of the large amplitude of the oscillations and their correlation with the Landau levels, this new magnetic quantum effect provides a sensitive method for the determination of band parameters. Further theoretical and experimental studies of this effect should also give valuable information on the electron-electron interaction in magnetic fields.

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Focusing of Intense Ion Beams by Radiation Cooling in a Magnetic Mirror

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It is shown that a space-charge–neutralized intense ion beam can be focused down to diameters of $\sim 10^{-1}$ cm by injection into a magnetic mirror through the combined action of the magnetic field and nonadabatic radiative energy losses. These intense tightly focused beams may be important for the eventual ignition of thermonuclear microexplosions.

Intense ion beams can be produced in high-voltage diodes by a variety of methods similar to the generation of intense relativistic electrons.[1-4] The attainable ion current density j is

$$j = (2q/M)^{1/2} V^{3/2} / 9\pi d^2, \qquad (1)$$

where q and M are the charge and mass of the ions, V the diode potential, and d the diode gap. Since $j = n_0 q v$, where n_0 is the initial ion number density and v the ion velocity, and $(M/2)v^2 = qV$, one has

$$n_0 = V / 9\pi q d^2. \qquad (2)$$

Assume $V = 3\times 10^6$ V $\simeq 10^4$ esu, $d = 0.1$ cm, and