PROC. 15TH INT. CONF. PHYSICS OF SEMICONDUCTORS, KYOTO, 1980
J. PHYS. SOC. JAPAN 49 (1980) SUPPL. A p. 623–626

SPIN RELAXATION OF CONDUCTION ELECTRONS IN P-TYPE SEMICONDUCTORS

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Spin-relaxation time of photoelectrons in p-type GaAs and GaSb has been measured by optical spin orientation techniques in wide range of doping and temperatures. Spin relaxation of thermalized electrons has been established to be governed by two mechanisms: Bir-Aronov-Picus' mechanism and D'yakonov-Perel' mechanism. The characteristic features of these mechanisms are shown and their efficiencies are determined.

1. Introduction

Optical pumping experiments have stimulated an increasing interest to the problem of conduction electron spin relaxation (SR) in p-type semiconductors. In early works the main mechanism considered was that of Elliott-Yafet [1] which connects the SR of electrons with their momentum relaxation through the spin-orbit interaction. This mechanism was found [2] to govern SR of conduction electrons in InSb. But for a number of A_3B_5 compounds, such as GaSb [3], GaAs [4] and $GaAl_xAs_{1-x}$ [5], the efficiency of Elliott-Yafet mechanism proved to be too weak to explain the experimental values of SR times τ_{se}.

Further theoretical investigations have brought two new mechanisms of conduction electron SR. The lack of inversion symmetry in A_3B_5 compounds leads to a spin splitting of conduction band. D'yakonov and Perel [6] proposed a relaxation mechanism due to this splitting /DP mechanism/, and obtained the following expression for SR rate:

$$\tau_{se}^{-1} = \alpha \bar{\omega}_s^2 \tau_p \quad , \quad \bar{\omega}_s^2 \sim E^3, \qquad (1)$$

where α is constant of the order of unity, $\bar{\omega}_s^2$ characterises conduction band splitting, E is the free electron energy, τ_p is the momentum relaxation time. The typical feature of this mechanism is decrease of it's efficiency with doping due to decrease of momentum relaxation time.

The second mechanism, studied by Bir, Aronov and Picus [7], is due to the exchange interaction between electrons and holes /BAP mechanism/. For this mechanism the SR rate is given by:

$$(2\tau_{se})^{-1} = \frac{3}{64} (N_p a_B^3) \frac{\Delta^2}{\hbar E_B} \Phi\left(\frac{v_e}{v_h}, \tau_{sh}\right), \qquad (2)$$

where N_p is the acceptor concentration, a_B, E_B, Δ are Bohr radius, ionization energy and the exchange splitting of ground 1s state of free exciton. Function Φ depicts the role of electron-hole interaction time which depends on their velocities v_e, v_h and hole SR

time τ_{sh}.

Numerical estimates [8] show that DP and BAP mechanisms should dominate SR of thermalized electrons in a number of A_3B_5 compounds. This conclusion is confirmed by some experimental results. Recently Clark et al [4] have attributed the SR of electrons in moderately doped GaAs above 100°K to DP mechanism. The dominant role of BAP mechanism in GaSb at low temperatures was shown by us [9]. However, these first experiments have not completly clarified all characteristic features of these mechanisms and their efficiencies in different ranges of doping and temperatures.

In this paper we present the results of systematic measurements of SR time τ_{se} of thermalized photoelectrons in p-type GaAs and GaSb doped with 10^{17} - 10^{20} cm^{-3} of Zn at temperatures 4.2 - 450°K. The quantity τ_{se} has been measured by the optical spin orientation techniques [10] which enabled us to find times as short as 10^{-11} sec.

2. Experimental Results and Discussion

Figure (1) shows the variations of τ_{se} as function of doping.

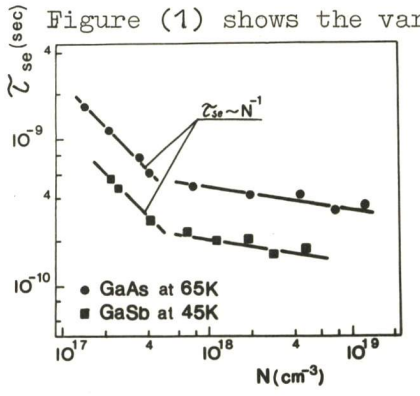

Fig. (1)

For both compounds τ_{se} exhibites the same behavior. At moderate doping τ_{se} decreases as N^{-1}, but at concentrations, exceeding the critical value of acceptor metallization N_0 1-2·10^{18}cm^{-3}, the decrease of τ_{se} becomes much slower. Decrease of τ_{se} with doping shows that DP mechanism is not operative here. At the same time the observed behavior of τ_{se} is in accordance with the theoretical predictions for BAP mechanism. Slowing of τ_{se} decrease at $N_p > N_0$, where holes become degenerated, is explained by the Pauli principle limitation of the effective number of holes interacting with electrons.

In the case of degenerate holes eq. (2) becomes:

$$(2\tau_{se})^{-1} = \frac{1}{\tau_0}\,\frac{3}{2}\,\frac{v_e\,T}{v_F\,E_F}\,, \qquad \tau_0^{-1} = \frac{3}{64}\,(N_p a_B^3)\,\frac{\Delta^2}{\hbar E_B}\,. \qquad (3)$$

This expression is obtained for the case, when electron velocity exceeds the hole velocity at Fermi surface $v_e > v_F$. For thermalized electrons $v_e \sim T^{1/2}$ so that τ_{se} should vary with temperature as $T^{3/2}$.

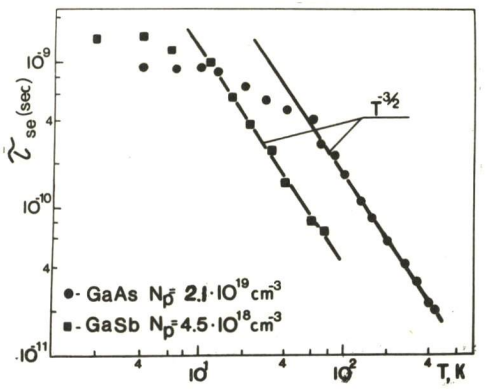

Fig. (2)

The temperature dependences of τ_{se} for degenerated GaAs and GaSb are shown in Fig.(2). It is seen that in wide temperature range the experimental results fit the predicted low. The agreement between the experiment and theory is achieved at the following values of exchange splitting constants 6·10^{-5}eV for GaAs and 4·10^{-5}eV for GaSb.

The saturation of SR at low temperatures cannot be explained by the transition to the case of slow electrons $v_e < v_F$, since here theory

predicts even more strong temperature dependence $T^{-5/2}$. The saturation is possibly related to incomplete thermalization of photoelectrons during lifetime. The optical spin orientation techniques permits to measure electron lifetimes simultaniosly with SR time. In degenerated crystals lifetimes were practicaly independent on doping and equal to $2.7 \cdot 10^{-10}$ sec. in GaAs and $4.3 \cdot 10^{-10}$ sec. in GaSb. According to Aronov estimations, these values are comparable or even less then the energy relaxation times of electrons at the bottom of conduction band at low temperatures.

In connection with this we would like to mention the first attempt to reveal the BAP mechanism [8]. In that paper temperature dependence of τ_{se} was investigated in GaAs with $N_p = 4 \cdot 10^{18} cm^{-3}$ which doping level corresponds already to degenerated case. The temperature dependecce found $\tau_{se} T^{-1/2}$ /Fig.(3)/ disagrees with the theory for degenerated case. However, our experimental results for GaAs with the same doping represented in Fig.(3) reproduce that of Fig.(2). The discrepancy between results of [8] and ours is possibly related to even stronger "heating" of photoelectrons in sample studied in [8], what is in accordance with shorter electron lifetime in this sample $6 \cdot 10^{-11}$ sec. The other possible reason can be additional SR mechanism, e.g. relaxation on accidental paramagnetic impurities.

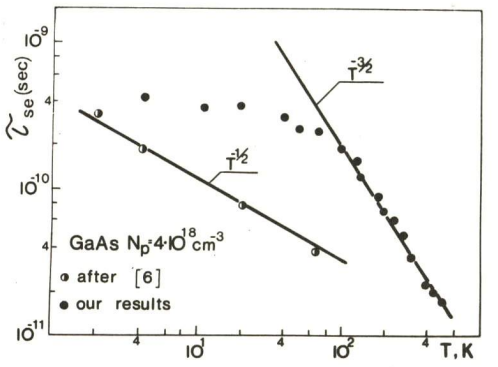

Fig. (3)

In the case of nondegenerated holes eq.(2) becomes:

$$(2\tau_{se})^{-1} = \frac{1}{\tau_o} \varkappa \left[\frac{N_p - p}{N_p} + \frac{p}{N_p} |\psi(o)|^4 \right], \qquad (4)$$

where $|\psi(o)|^4 = \left| \frac{2\pi}{\varkappa} \frac{1}{1 - e^{-\frac{2\pi}{\varkappa}}} \right|^2$, $\varkappa = \left(\frac{E}{E_B} \right)^{1/2}$.

Two terms in brackets represent the contributions in SR due to electron interaction with localized on acceptors and free holes. $|\psi(o)|^2$ is the Zommerfeld factor enhancing the free hole contribution. It is seen that SR rate does not have simple power dependence on temperature. Moreover, in the case of complete ionization of acceptors with temperature the increase of electron energy should even decrease the SR rate:

$$\tau_{se} \sim \varkappa \sim E^{1/2}. \qquad (5)$$

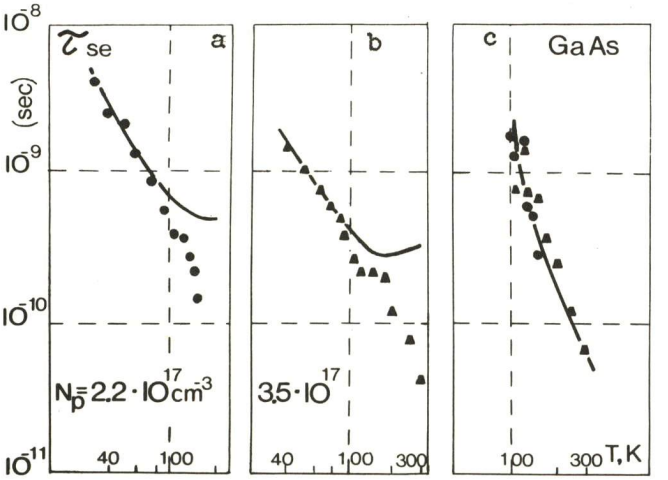

Fig. (4 a,b,c)

Variation of τ_{se} in two moderately doped

GaAs crystals is shown in Fig.(4 a,b). The same temperature dependence of τ_{se} was also observed in GaSb [9].

For GaAs we have found that the experimental data on Fig.(4 a,b) up to 100°K could be accurately described by theoretical expression (4) using the exchange splitting constant $\Delta = 6 \cdot 10^{-5}$ eV determined in degenerated case. In sample with higher doping /Fig.(4 b)/ even the saturation of SR rate can be noticed.

The sharp increase of SR rate above T = 100°K should be attributed to the appearance of additional SR mechanism. Using the theoretical estimates for BAP relaxation efficiency we can educe from experimental data on Fig.(4 a,b) the values of SR times for this additional mechanism $1/\tau_{se} = 1/\tau_{se,exp} - 1/\tau_{es,\ BAP\ th}$. These values shown in Fig.(4 c) can be well described by expression (1) for the SR rate through DP mechanism. The good agreement between experimental data and theory /full line in Fig.(4 c)/ is achieved with reasonable for GaAs value of $\overline{\omega}_s^2 = 4 \cdot 10^{18}$ cm^{-3} /rad.^{2} sec.$^{-2}$ meV.$^{-3}$ /: The change of the theoretical curve inclination is due to the temperature dependence of τ_p [11]. So, obtained results show that revealed at high temperatures SR mechanism should be the DP mechanism. This conclusion confirms inference of [4] about the dominant role of DP mechanism in moderately doped GaAs at high temperatures.

3. Conclusion

We have shown that spin relaxation of thermalized conduction electrons in p-type GaAs and GaSb is well described by theoretically predicted DP and BAP mechanisms in wide range of doping and temperatures. The BAP mechanism is the dominant one in highly doped crystals in all investigated temperature range. In moderately doped crystals efficiency of DP mechanism becomes comparable to that of BAP and even higher for high temperatures.

4. Acknowledgments

We wish to thank A.G.Aronov and G.E.Picus for extremely valuable discussions.

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