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XIII-7. Electric Field Effect on the Spin-Lattice Relaxation of Donor Electrons in Silicon

K. MORIGAKI and J. M. WINTER

Service de Physique du Solide et de Résonance Magnétique
Centre d'Etudes Nucléaires de Saclay, France

The spin-lattice relaxation times of donor electrons were measured at 1.3°K in compensated phosphorus-doped silicon and uncompensated ones under the application of a static electric field. And increase of the relaxation rate of donor electrons was observed with increasing the magnitude of the electric field. For high electric field the change of the relaxation rate may be due to the interaction of donor electrons with the free carriers. For weak electric field the experimental results are discussed; the donor electrons remain localized but the electric field changes the concentration dependent part of their relaxation times.

§ 1. Introduction

Spin-lattice relaxation of donor electrons in compensated phosphorus-doped silicon and uncompensated ones has been investigated under the application of a static electric field at 1.3°K. Some results on the measurements of the relaxation time are presented in this report. According to the magnitude of the electric field, two regions of variation for the relaxation rate may be distinguished. In the high electric field region, some of the donor electrons are excited into the conduction band through the impact ionization process. The relaxation rate of donor electrons can be determined by the interaction with free carriers. Pines, Bardeen, and Slichter[1] considered the relaxation mechanism due to the exchange scattering of free carriers by donor impurities. Their theory can be applied to our case to understand the relaxation behavior of localized donor electrons in electric field. The relaxation rate of free carriers was calculated by Elliott[2] and plays an important role in understanding the change of the relaxation times of localized donor electrons with electric field. In the weak electric field region the relaxation mechanism is related to that operating in the case without electric field. Without electric field the concentration dependent relaxation mechanism has been investigated by several authors.[3-7] The rapid relaxing centers such as ionized donor pairs are believed to contribute importantly to the relaxation process of donor electrons.[4,7] In this case, the excitation energy of donor spins associated with isolated donors may be transferred by spin diffusion or hopping motion to the rapid relaxing centers. The observed change of the relaxation rate of donor electrons with electric field in the weak electric field region will be discussed from the above model for the relaxation mechanism.

§ 2. Experimental Method

The spin resonance experiments were performed at 1.3°K by using the conventional bridge type spectrometer operating at X-band. The spin-lattice relaxation time was measured as follows: The thermal equilibrium was disturbed by completely saturating the spin system. The recovery of the signal after saturating the spin system was observed by using a weak microwave power. The relaxation time T_s was then obtained from an expression $M(t)=M_0[1-\exp(-t/T_s)]$, where M_0 is the magnetization at thermal equilibrium of the spin system. In those cases in which one observed a deviation from this exponential form the relaxation time was arbitrarily defined as the time taken for the magnetization to build up to $(1-1/e)$ of its final value. The dependence of the relaxation time on magnetic field was measured by keeping the spin system at a given magnetic field for an appropriate time after saturating the spin system at 3.5 kG field.

Characteristics of the samples used in this experiment are presented in Table I, where N_D and N_A are the concentration of phosphorus and boron respectively, and K is the degree of compensation, N_A/N_D.

The electrode was made as follows: The faces at both ends of the sample were first evaporated by Sb-doped Au in vacuum and then annealed in vacuum at 700°C being followed by an immediate quenching. After then, the evaporated

Table I. Sample characteristics.

Sample No.	N_D (No./cm³)	N_A (No./cm³)	K
1	4×10^{16}	8×10^{15}	0.2
2	4×10^{16}	1.6×10^{16}	0.4
3	6×10^{16}		
4	6×10^{16}	8×10^{15}	0.13
5	6×10^{16}	2×10^{16}	0.33

surfaces were plated by Rh and soldered by In. The static electric field was applied to the sample along its longest dimension (~8 mm). No attempt was made to apply the electric field along any particular crystallographic orientation, but it was applied along a direction perpendicular to the static magnetic field. The voltage—current characteristics were also measured.

§ 3. Experimental Results

Figure 1 shows the electric field dependence of the relaxation time T_s observed at 3.5 kG.

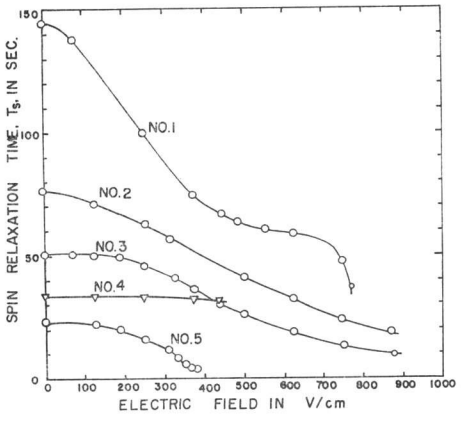

Fig. 1. The relaxation time T_s vs. the applied electric field.

In the sample No. 1 the relaxation time decreases gradually with increasing the electric field and it seems to reach a stationary value, and then it decreases rapidly with an increase of the electric field. The last stage of the decrease of the relaxation time corresponds to the rapid increase of the current flowing through the sample. A more compensated sample (No. 2) with the same donor concentration as the above one exhibits a gradual decrease of the relaxation time with increasing the electric field. In the weak electric field the relaxation time does not change with electric field in the sample No. 3 and it does not show a great change in the sample No. 5. The sample No. 4 is different from other samples in the relaxation behavior for electric field, which shows a little change with electric field in spite of the increase of the current. In Fig. 2 the relaxation rate observed in the sample

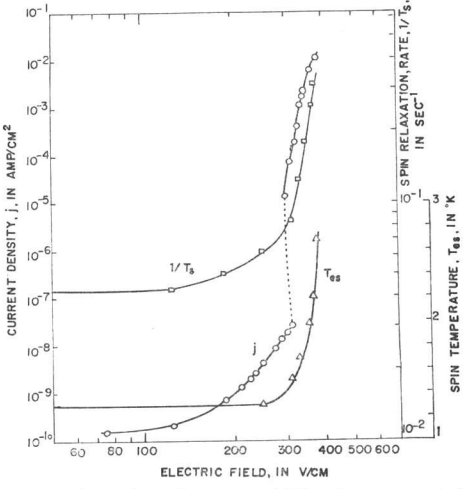

Fig. 2. The relaxation rate $1/T_s$, the current density j, and the spin temperature T_{es} vs. the applied electric field in the sample No. 5.

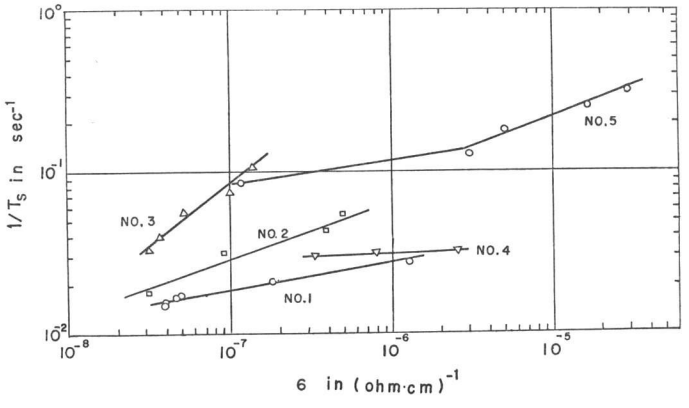

Fig. 3. The relaxation rate $1/T_s$ vs. the electrical conductivity σ.

No. 5 is plotted against the electric field together with the current density observed.*

In the high electric field in which some of donor electrons are ionized from donor impurities into the conduction band the observed relaxation rate can be expressed by the equation, $1/T_s \propto \sigma^{\beta}$, against the conductivity, σ, as shown in Fig. 3. The values of β are given as follows: The sample No. 1: 0.17, No. 2: 0.35, No. 3: 0.76, No. 4:0.026, No. 5: 0.14 ($10^{-7} \lesssim \sigma \lesssim 3\times10^{-6}$), 0.38 ($3\times10^{-6} < \sigma < 3\times10^{-5}$. In the case of the sample No. 5 the spin temperature was raised with electric field above a certain value of the field as shown in Fig. 2.** In the other samples the change of the spin temperature was below 10% even in the maximum electric field used.

The magnetic field dependence of the relaxation rate was measured for the sample No. 1 which exhibited a long relaxation time suitable for such a measurement. Except in the high magnetic field ($\sim$9 kG) the change of the relaxation rate with electric field was found.

§ 4. Discussion

The experimental results show that the mechanism underlying the spin-lattice relaxation under the static electric field may be divided into two parts according to the magnitude of the electric field. First, we shall consider the relaxation mechanism operating in the high electric field. In this case some of donor electrons are excited into the conduction band through the impact ionization process and they contribute to electrical conduction as free carriers. Then, we can expect that the interaction of donor electrons with free carriers causes a great increase of the relaxation rate of donor electrons. Pines, Bardeen, and Slichter[1] considered the relaxation mechanism due to the exchange scattering of free carriers by donor impurities. According to their theory the relaxation rate of donor electrons, $1/T_s$, can be expressed by the following equation in our case,

$$1/T_s = W_f n/N, \qquad (1)$$

where W_f is the relaxation rate of free carriers, and n and N are the concentration of free carriers and donor electrons respectively. The spin-lattice relaxation of free carriers in semiconductors arises from the impurity scattering at low temperatures. The relaxation rate of free carriers due to this mechanism has been calculated by Elliott[2] in the case of ionized impurity scattering. In our case the number of free carriers is very small compared with the donor concentration, but their temperatures are different from the lattice temperature above the critical electric field. Then, the relaxation rate W_f is given by

$$W_f \sim \frac{1}{\tau_R}\left(\frac{2m^* kT_e (g-2)^2 a_0^{\,2}}{\hbar^2}\right), \qquad (2)$$

where τ_R is the relaxation time of free carriers associated with the electrical conductivity, a_0 is the atomic radius, T_e is the temperature of free carriers, and the other notations are usual ones. The above expression for the relaxation rate W_f may be applied to the case of neutral impurity scattering which can be seen in non-compensated samples at liquid helium temperatures. The expression given by eq. (1) can be written as a function of the conductivity, σ, instead of n to be compared with the observed dependence of $1/T_s$ on σ;

$$1/T_s = W_f \sigma/|e|\mu N, \qquad (3)$$

where μ is defined as the mobility of free carriers. The relaxation rate W_f is also related to the mobility through eq. (2). The change of mobility with electric field has been calculated by Yamashita[9] in relation with the electric breakdown observed in germanium at low temperatures. His expression for the mobility is too complicated to be written down in a simple formula. So, here we simplify the expression for the mobility to understand qualitatively the relaxation behavior of donor electrons in a high electric field. In the case of ionized impurity scattering the mobility depends on the energy of free carriers in such a manner as $\mu \propto \varepsilon^{3/2}$. Then, the relaxation rate of donor electrons depends on the mobility in the following manner: $1/T_s \propto \sigma/\mu^{4/3}$. The increase of μ with electric field leads to a weaker dependence of $1/T_s$ on σ than that expected by constant mobility. On the other hand, the neutral impurity scattering gives rise to the energy independent mobility, so the relaxation rate $1/T_s$ is proportional to $(T_e/\mu^2)\sigma$. The observed change of $1/T_s$ in non-compensated samples gave its stronger dependence on σ than that observed in other compensated samples. In non-compensated samples the mobility is determined by neutral impurity scattering at liquid helium temperatures. The above consideration

* A negative resistance has been observed in the sample No. 5 as shown in Fig. 2.

** An increase of the spin temperature of donor electrons with electric field has been observed by Feher[8] in phosphorus-doped silicon.

leads to a stronger dependence of $1/T_s$ in non-compensated samples on σ than that in compensated ones in agreement with the observation. The different behaviors of the relaxation rate $1/T_s$ among the samples can be understood in terms of eqs. (2) and (3), in which the appropriate increase of the mobility as well as the scattering mechanism is taken into account. However, we have to postpone the quantitative analysis of the relaxation rate $1/T_s$ until the change of the mobility with electric field will be measured.

Next, we shall discuss the relaxation mechanism operating in a weak electric field. Jerome's experiment[6] on the magnetic field dependence of $1/T_s$ without electric field seems to show that the relaxation of donor electrons in compensated samples with $N_D=6\times10^{16}\text{cm}^{-3}$ is determined by ionized donor pairs working as the rapid relaxing centers in such a manner as expected from Sugihara's theory,[7] but in non-compensated sample with $N_D=6\times10^{16}\text{cm}^{-3}$ and in compensated samples with $N_D=4\times10^{16}\text{cm}^{-3}$ the dependence of $1/T_s$ on magnetic field cannot be understood by Sugihara's theory. In the former case one can expect the rapid hopping process, but in the latter cases the bottleneck seems to lie in the transfer process of the excitation energy associated with donor spins from isolated donor sites to ionized donor pairs. The change of the relaxation rate $1/T_s$ in compensated samples with $N_D=4\times10^{16}\text{cm}^{-3}$ with a static electric field might be due to a change of the transfer process from spin-diffusion to hopping motion in which ionized donor pairs can contribute greatly to the relaxation process. Also, the change of the relaxation rate of ionized donor pairs themselves may give rise to an increase of $1/T_s$.

The relaxation rate $1/T_s$ measured at 9 kG in the sample No. 1 in the electric field 250 V/cm did not show a change compared to that without electric field. In such a high magnetic field the relaxation rate of donor electrons can be understood well by the theory of Hasegawa[10] and Roth[11] that is concerned with the isolated donor impurity level. If impurity levels are not affected greatly by the electric field we use, no change of the relaxation rate with electric field can be expected in agreement with the observation.*

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* This consideration is supported by the fact that no change of the hyperfine splitting due to phosphorus nuclei has been observed in the electric field used in this experiment.