

Resistance changes induced by electron-spin resonance in ion-implanted Si:P system

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The ESR-induced changes in the dc resistance, $\Delta\rho/\rho|_{\text{ESR}}$, of P-ion-implanted silicon have been observed for the first time. The transfer of absorbed Zeeman energy at liquid-He temperature has been investigated. The $\Delta\rho/\rho|_{\text{ESR}}$ signals observed were a narrow line with a g value of 1.9988 for light-dose implantation and a new broad line with a little larger g value for heavy-dose implantation. The line shape of these $\Delta\rho/\rho|_{\text{ESR}}$ signals was Lorentzian as well as the ESR signal, but the linewidth $\Delta H_{1/2}$ of the broad $\Delta\rho/\rho|_{\text{ESR}}$ signal was about 10 times as broad as the ESR linewidth. It is suggested that the anomalously broad line of $\Delta\rho/\rho|_{\text{ESR}}$ originates from the transfer of the Zeeman energy absorbed by the localized donor electrons at the tail regions with low donor concentration ($5 \times 10^{17} < N_D \leq 1.5 \times 10^{18}$ P/cm³) to the layer with intermediate donor concentration ($1.5 \times 10^{18} < N_D \leq 3.7 \times 10^{18}$ P/cm³) where the resistance changes take place. This transfer is caused by the existence of the peak regions with high donor concentration ($N_D \geq 2 \times 10^{19}$ P/cm³) which act as Zeeman energy absorbers.

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I. INTRODUCTION

The ESR-induced changes in the dc electrical resistance, $\Delta\rho/\rho|_{\text{ESR}}$, have been measured by many workers¹⁻⁵ for n -type semiconductors (e.g., InSb, Si, and Ge) at low temperature to investigate the spin-dependent conductivity, the relaxation mechanism of the Zeeman energy, and the electronic state of donor atoms. In this method, the static magnetic field is slowly swept at a constant microwave frequency in the same way as the usual ESR method, and the change in resistance is detected at the resonant field corresponding to the ESR signal. It was shown by Guéron and Solomon¹ that for very small samples the method of measuring $\Delta\rho/\rho|_{\text{ESR}}$ should be much more sensitive than the usual ESR method. Therefore, it is useful to apply the $\Delta\rho/\rho|_{\text{ESR}}$ method to ion-implanted semiconductors which contain a small number of spins.⁶

For bulk Si:P (Si doped uniformly with phosphorus), many investigations have been done at the intermediate concentration region ($1.5 \times 10^{18} < N_d \leq 3.7 \times 10^{18}$ P/cm³)^{2,3} and the high- (I) concentration region ($3.7 \times 10^{18} < N_d < 2 \times 10^{19}$ P/cm³).⁴ It has been impossible to observe the $\Delta\rho/\rho|_{\text{ESR}}$ at the low-concentration region ($N_d \leq 1.5 \times 10^{18}$ P/cm³) and high- (II) concentration region ($N_d \geq 2 \times 10^{19}$ P/cm³).²⁻⁴ The energy reservoir of interest is considered to be the kinetic-energy system of the delocalized donor electrons coupled to the donor electron spins by the spin-orbit interaction.¹⁻³ The power fed by the donor spins increases the kinetic energy of the electrons, and this is detected by an increase in the mobility, that is, a decrease in dc resistance.

In previous papers,⁶⁻⁸ the ESR study at 77 K was performed on an ion-implanted Si:P system, in which the phosphorus distribution is nearly Gaussian, as shown in Fig. 1. In the system investigated, delocalized donor electrons (conduction electrons) move around very rapidly in the whole implanted layer during the virtual spin-lattice relaxation time $\tau_1(x_i)$ of the i th layer Δx_i between x_i and $x_i + \Delta x_i$. That is, the implanted layer is much thinner than the spin mean free path, $\delta_{\text{eff}} = (\frac{2}{3}v_F\lambda\tau_1)^{1/2} = \text{several } \mu\text{m}$, where the v_F is the mean value of the Fermi velocity, λ is the electronic mean free path, and τ_1 is the mean value of $\tau_1(x_i)$. Therefore, an effective spin-lattice relaxation time $T_{1\text{eff}}$ of the implanted layer is an average of $\tau_1(x_i)$ over the whole implanted layer and can be determined experimentally from the linewidth ΔH_{msl} of the Lorentzian ESR spectrum as $T_{1\text{eff}} \doteq T_2 = 2/\sqrt{3}\gamma\Delta H_{\text{msl}}$.⁷ If donor electrons were completely localized and there were no energy transfers, $\tau_1(x_i)$ would be unchanged and the ESR linewidth would be Gaussian because of the superposition of signals with different linewidths, $\Delta H_{\text{msl } i} = 2/\sqrt{3}\gamma\tau_1(x_i)$. $T_{1\text{eff}}$ is thought to be dominated by a extremely thin layer with the shortest $\tau_1(x_i)$.^{7,8}

At liquid-helium-temperature (LHeT) regions, the system becomes different from that at 77 K; i.e., two kinds of layers coexist in the ion-implanted Si:P system, as shown in Fig. 1. One is the layer at peak regions of the impurity profile, where the donor concentrations are higher than that for the metal-insulator (Mott) transition ($N_c = 3.7 \times 10^{18}$ P/cm) and delocalized donor electrons behave like free electrons.⁹ Thus, the layer shows metallike conduction. The other is the layer at the tail regions, where the donor concentrations are lower than N_c and the donor electrons are completely localized.⁹ Thus, the layer becomes an insulator

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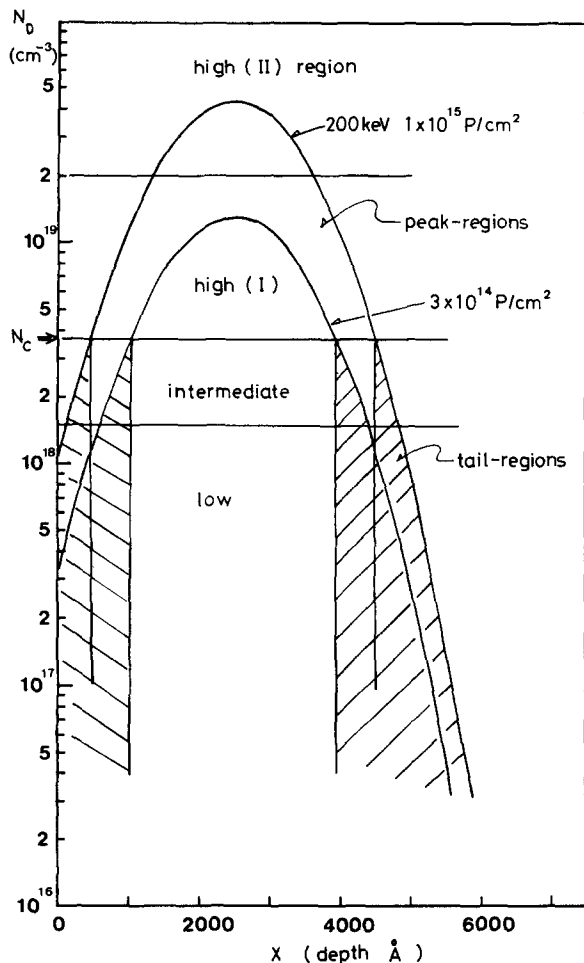


FIG. 1. The depth profiles of phosphorus atoms in silicon annealed at 900 °C for 15 min after implantation of 200-keV P⁺, 1×10^{15} /cm², and 200-keV P⁺, 3×10^{14} /cm², respectively, calculated from $N_D(x) = N_{\text{dose}} [2\pi(\sigma^2 + 2Dt)]^{-1/2} \exp[(x - R_p)^2 / (2\sigma^2 + 4Dt)]$, where D (900 °C) = 1×10^{-11} cm² sec⁻¹, $t = 15$ min, and N_{dose} is the implanted dose. The concentrations of P atoms are divided into four regions; i. e., high- (II) and high- (I) concentration regions above the critical concentration N_c for Mott transition and intermediate and low concentration regions below N_c (see Refs. 9, 11, and 12). Regions shaded with oblique lines indicate the tail, regions which consist of both the intermediate- and low-concentration regions.

at low temperature. The importance of the Zeeman energy transfer between these two kinds of layers seems to be unclear in ion-implanted semiconductors.

In this paper, we investigate the relaxation mechanism at LHeT through the transfer of absorbed Zeeman energy between two kinds of layers by the methods of both $\Delta\rho/\rho|_{\text{ESR}}$ and ESR. We believe that this is the first observation of $\Delta\rho/\rho|_{\text{ESR}}$ in ion-implanted samples. The origin and the mechanism of $\Delta\rho/\rho|_{\text{ESR}}$ are discussed.

II. EXPERIMENTAL PROCEDURE

Phosphorus-ion implantation in silicon was done at an energy of 200 keV with doses of 1×10^{14} to 3×10^{15} P/cm² and at an energy of 50 keV with doses of 1×10^{14} to 1×10^{15} P/cm² at room temperature. The samples were annealed in a vacuum of about 10^{-6} Torr at 900 °C for 15 min in order to obtain substitutional P in nearly damage-free Si (ion-implanted Si:P). For 200-keV P⁺,

the average projected range R_p and the projected standard deviation of the range σ are about 2500 and 800 Å, respectively, and for 50-keV P⁺ these are 600 and 250 Å, respectively.¹⁰

Contacts were formed by depositing and alloying the Au-Sb (0.5 wt% antimony) to measure the dc resistance. At room temperature and 77 K, the I - V characteristic was Ohmic, but at LHeT (1.6–4.2 K), only about one-third of the samples showed Ohmic character.

The dc resistance changes induced by ESR, $\Delta\rho/\rho|_{\text{ESR}}$, was obtained by measuring the changes of the dc voltage across the sample at the microwave frequency of 9 GHz at 4.2 and 1.6 K. The spectrometers used were of a balanced mixer type. Samples were mounted on a Teflon holder at the center of the TE₁₀₂ rectangular cavity, where the oscillating magnetic field was strongest. The microwave power was modulated in a square waveform with a frequency of 10 or 100 kHz. The signal corresponding to the change of the voltage across the sample due to ESR, $\Delta\rho/\rho|_{\text{ESR}}$, or due to only microwave irradiation at off resonance, $\Delta\rho/\rho|_{\text{off}}$, was phase detected through a lock-in detector, and, in some cases, an accumulator was used to improve the S/N ratio. The $\Delta\rho/\rho|_{\text{off}}$ is dependent on the electronic state of donor electrons.⁴ Microwave power and electrical field across the sample were varied from 0.4 to 50 mW and from 20 mV/cm to 10 V/cm, respectively. The bulk Si:P doped at 1.8×10^{18} P/cm³ was also measured as a standard sample for determining a sign of the resistance changes.

Since the cavity Q value was much lower for the $\Delta\rho/\rho|_{\text{ESR}}$ measurement, it was difficult to obtain the ESR signal with a good S/N ratio. Therefore, both a balanced mixer type and a conventional reflection-type ESR spectrometers at 9 GHz were employed for ESR measurements at 4.2 and 1.6 K. Cavities used were of the type of rectangular TE₁₀₁ or cylindrical TE₁₁₁. Several samples were mounted at the bottom of the cavity to improve the S/N ratio further.

III. EXPERIMENTAL RESULTS

In the case of the bulk Si:P with the donor concentration of 1.8×10^{18} P/cm³, the signs of $\Delta\rho/\rho|_{\text{ESR}}$ and $\Delta\rho/\rho|_{\text{off}}$ were negative. A negative sign means the decrease of electrical resistance,^{2,3} which was confirmed by measuring directly a change of the voltage across the sample. The linewidth $\Delta H_{1/2}$ of $\Delta\rho/\rho|_{\text{ESR}}$ was completely equal to the ESR linewidth $\Delta H_{1/2}$ ($=\sqrt{3}\Delta H_{\text{msl}}$), as shown in Fig. 2(a).

The ESR and the $\Delta\rho/\rho|_{\text{ESR}}$ signals observed in ion-implanted Si:P showed a single Lorentzian line shape as illustrated in Figs. 2(b) and 2(c). As expected, the $\Delta\rho/\rho|_{\text{ESR}}$ method was much more sensitive for ion-implanted Si:P than the usual ESR. All implanted samples showed a negative sign for $\Delta\rho/\rho|_{\text{ESR}}$ and a positive sign for $\Delta\rho/\rho|_{\text{off}}$. These behaviors are the same as those of bulk Si:P⁴ with the donor concentrations above the critical concentration for the metal-insulator transition (3.7×10^{18} P/cm³).

The observed $\Delta\rho/\rho|_{\text{ESR}}$ signals showed two kinds of lines. For ion-implanted Si:P with 200-keV P and a

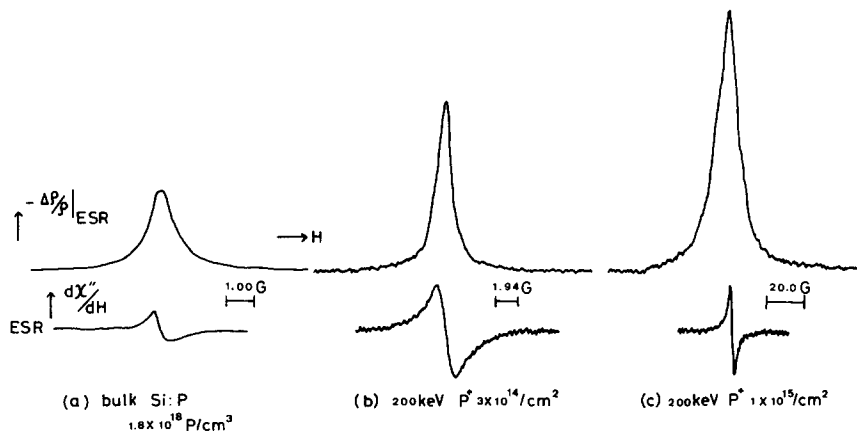


FIG. 2. Typical $\Delta\rho/\rho|_{\text{ESR}}$ and ESR signals observed at 4.2 K for each sample. The ESR signal is the derivation of the absorption line and is proportional to $d\chi''/dH$. For $\Delta\rho/\rho|_{\text{ESR}}$, the signals in (a), (b), and (c) were observed with microwave power of 10, 30, and 30 mW and the dc electric field of 10, 8, and 10 V/cm, respectively. All the signs of $\Delta\rho/\rho|_{\text{ESR}}$ are negative (-), while the signs of $\Delta\rho/\rho|_{\text{off}}$ were (-), (+), and (+) for (a), (b), and (c), respectively.

dose of $3 \times 10^{14}/\text{cm}^2$, the $\Delta\rho/\rho|_{\text{ESR}}$ signal was a narrow line with a g value of 1.9988, as shown in Fig. 2(b). The narrow line agrees with the ESR line and is the same with the $\Delta\rho/\rho|_{\text{ESR}}$ observed in bulk Si:P.⁴ However, for ion-implanted Si:P samples with a higher effective donor concentration N_D^* ,⁶ a new broad signal of $\Delta\rho/\rho|_{\text{ESR}}$ was observed. The signal showed a much broader line with a little larger g value than that of the ESR signal as shown in Figs. 2(c) and 3. The broader lines of $\Delta\rho/\rho|_{\text{ESR}}$ have a width of between 15 and 20 G, while the ESR linewidth $\Delta H_{1/2}$ has much smaller value as shown in Fig. 3. Therefore, the new signal is found not to be induced by the ESR of delocalized electrons at peak regions. It should be also noted that the line shape is Lorentzian though it is a little asymmetric. At a N_D^* of $8.5 \times 10^{18} \text{ P/cm}^3$, both the narrow and the broad lines of $\Delta\rho/\rho|_{\text{ESR}}$ were observed. The linewidth $\Delta H_{1/2}$ of $\Delta\rho/\rho|_{\text{ESR}}$ decreases with increasing N_D^* above $8.5 \times 10^{18} \text{ P/cm}^3$. No signal of $\Delta\rho/\rho|_{\text{ESR}}$ was detected at a N_D^* of $8.5 \times 10^{19} \text{ P/cm}^3$.

The ESR linewidth of ion-implanted Si:P at LHeT

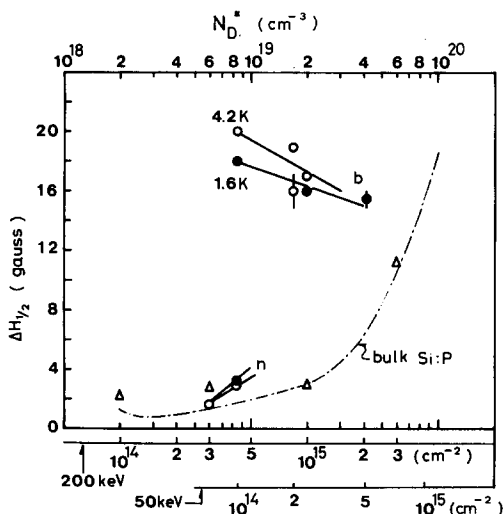


FIG. 3. Experimental linewidth $\Delta H_{1/2}$ of $\Delta\rho/\rho|_{\text{ESR}}$ and ESR as a function of N_D^* . n and b represents the narrow and a broad line of $\Delta\rho/\rho|_{\text{ESR}}$, respectively. The ESR linewidth at 4.2 K for Si:P with the 200-keV implant is also shown by Δ , which is compared with the line of dots and dashes indicating the results of the ESR linewidth in bulk Si:P.^{11,12}

agrees with that of bulk Si:P¹¹ above an N_D^* of about $2 \times 10^{19} \text{ P/cm}^3$, as can be seen in Fig. 3. However, below $2 \times 10^{19} \text{ P/cm}^3$, the former is broader than the latter. The difference seems to arise from the existence of localized donor electrons at the tail regions, i.e., the energy transfer from the tail regions to the peak regions is much slower than the inverse relaxation rate $\tau_1(x_i)^{-1}$ of the peak regions.

The dependence of the intensity of $\Delta\rho/\rho|_{\text{ESR}}$ on N_D^* is shown in Fig. 4. The intensity for the narrow line decreases with increasing N_D^* , which agrees with the results in bulk Si:P.⁴ On the other hand, the intensity for the broad line seems to increase with increasing N_D^* .

IV. DISCUSSION

The anomalously broad line of $\Delta\rho/\rho|_{\text{ESR}}$ is not observed in bulk Si:P²⁻⁴ but in ion-implanted Si:P. The latter differs from the former in having the tail regions with localized donor spins, as shown in Fig. 1. The layer with low, intermediate, high (I), and high (II) concentration regions of donor atoms are hereafter called LR, IR, HR(I), and HR(II), respectively.

The questions now are what is the origin of ESR which causes the broad line, and how are the resistance

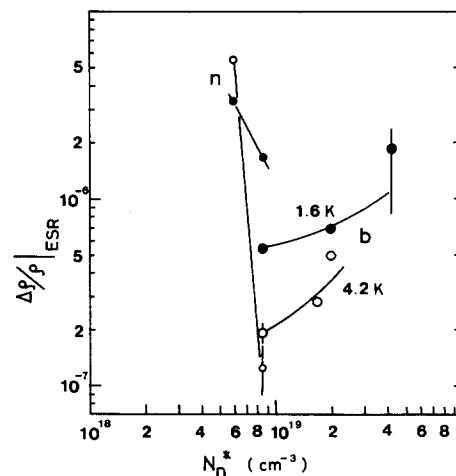


FIG. 4. Experimental intensity of $\Delta\rho/\rho|_{\text{ESR}}$ as a function of N_D^* . The microwave power level is 30 mW, and the intensity is the maximum value as a function of electrical field.

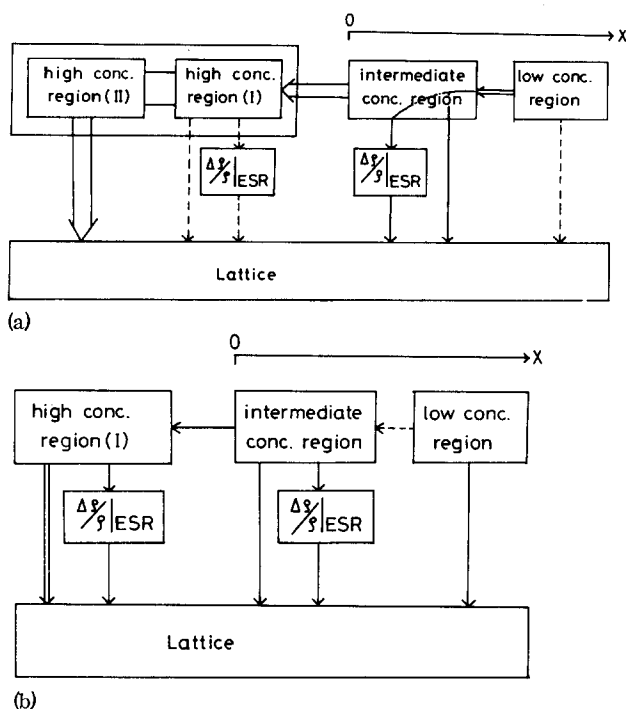


FIG. 5. The block diagram for the relaxation process (or energy transfer) of absorbed Zeeman energy. The broken lines show the relaxation path through which little energy flows into the lattice. (a) and (b) indicate that the broad line of $\Delta\rho/\rho|_{\text{ESR}}$, which corresponds to the ESR at LR, is observed for the case of extremely short $T_{1\text{eff}}$, and that the narrow line is observed for the case of relatively long $T_{1\text{eff}}$, respectively.

changes induced by the ESR. Here we propose a model for the new broad line of $\Delta\rho/\rho|_{\text{ESR}}$ due to ESR^{11,12} of the localized donors at LR ($5 \times 10^{17} < N_D \leq 1.5 \times 10^{18}$ P/cm³) and due to the transfer of the Zeeman energy absorbed there to IR ($1.5 \times 10^{18} < N_D < 3.7 \times 10^{18}$ P/cm³), where the resistance changes take place. This model

is characteristic of fast energy transfer induced by the existence of HR(II) ($N_D \gtrsim 2 \times 10^{19}$ P/cm²) which has the shortest $\tau_1(x_i)$ and so acts as a Zeeman energy absorber.

At HR(I) or HR(I) and HR(II), an effective spin-lattice relaxation time $T_{1\text{eff}}$ is determined as an average since the spin mean free path δ_{eff} is much greater than the thickness of HR. Therefore, the ion-implanted Si:P system is considered to be a system where the fast relaxing centers with the relaxing rate of $T_{1\text{eff}}^{-1}$ are added to the surface of the layer of IR. If so, it will depend on the rate of energy transfer to the surface whether the broad line appears.

For the ion-implanted Si with 200-keV P and a dose of 1×10^{15} P/cm³ (sample No. 1), a block diagram for the relaxation process of the absorbed Zeeman energy is shown in Fig. 5(a). It means that $T_{1\text{eff}}$ is determined at HR and that most of the Zeeman energy absorbed there is relaxed into the lattice system at the layer with the shortest $\tau_1(x_i)$ in HR(II). At relatively high temperature (77–300 K), $T_{1\text{eff}}$ is determined over the whole implanted layer as follows⁷:

$$T_{1\text{eff}}^{-1} = \left[\int_0^\infty \tau_1(x)^{-1} N_D(x) dx \right] \left[\int_0^\infty N_D(x) dx \right]^{-1} + \tau_p^{-1}, \quad (1)$$

where $N_D(x)$ is the depth profile of P, τ_p is the relaxing time due to the phonon-dependent process and is assumed to be independent of $N_D(x)$ at a certain temperature. Equation (1) shows that the implanted layer is one Zeeman system since δ_{eff} is much greater than the thickness of the implanted layer and that the Zeeman energy of each delocalized electron flows into the lattice through the many relaxing paths of

$$T_1(x_i)^{-1} = \frac{\tau_1(x_i)^{-1} N_D(x_i) \Delta x_i}{\sum_i N_D(x_i) \Delta x_i} \quad (i = 1, 2, \dots, n). \quad (2)$$

The energy relaxed at the i th layer, Δx_i , is proportional to the value of $T_1(x_i)^{-1}$ in Eq. (2). Although the rate of energy transfer greatly differs between HR and IR, the Zeeman energy absorbed at IR is thought to be

TABLE I. The mean values applied for four layers.

	HR(II)	HR(I)	IR	LR
Concentration of donors (cm ⁻³)	$n_1 = 3 \times 10^{19}$	$n_2 = 6 \times 10^{18}$	$n_3 = 2 \times 10^{18}$	$n_4 = 1 \times 10^{18}$
Virtual spin-lattice relaxation time at 4.2 K (sec) (Ref. 13)	$\tau_1(1) = 1 \times 10^{-8}$	$\tau_1(2) = 7 \times 10^{-8}$	$\tau_1(3) = 4 \times 10^{-7}$	$\tau_1(4) = 1 \times 10^{-6}$
Resistivity at 4.2 K (Ω cm) (Refs. 3, 4, and 14)	$\rho_1 = 7 \times 10^{-4}$	$\rho_2 = 5 \times 10^{-3}$	$\rho_3 = 5 \times 10$	$\rho_4 \gtrsim 10^6$
Resistance change induced by ESR at 4.2 K (Refs. 2–4) (at ~ 30 mW)	$\Delta\rho/\rho _{\text{ESR}} \lesssim 10^{-10}$	$\Delta\rho/\rho _{\text{ESR}} = 5 \times 10^{-7}$	$\Delta\rho/\rho _{\text{ESR}} = 2 \times 10^{-2}$...
Paramagnetic susceptibility at 4.2 K (cgs/g) (Ref. 11)	$\chi_0(1) = 3.3 \times 10^{-8}$	$\chi_0(2) = 2.9 \times 10^{-8}$	$\chi_0(3) = 4.6 \times 10^{-8}$	$\chi_0(4) = 3.7 \times 10^{-8}$
Thickness of the layer (\AA) ^a	$l_1 = \begin{cases} 0 \\ 2000 \end{cases}$	$l_2 = \begin{cases} 2500 \\ 2000 \end{cases}$	$l_3 = \begin{cases} 1000 \\ 1000 \end{cases}$	$l_4 = \begin{cases} 1500 \\ 1000 \end{cases}$
Resistance of the layer at 4.2 K (Ω)	$R_1 = \begin{cases} \dots^b \\ 3.5 \times 10 \end{cases}$	$R_2 = \begin{cases} 2 \times 10^2 \\ 2.5 \times 10^2 \end{cases}$	$R_3 = \begin{cases} 5 \times 10^6 \\ 5 \times 10^6 \end{cases}$	$R_4 \gtrsim \begin{cases} 6.6 \times 10^{10} \\ 1 \times 10^{11} \end{cases}$

^a l_1, l_2, l_3 , and l_4 are determined from the phosphorus distribution.

^b The values of the upper row and the lower row for l and R are those for sample Nos. 2 and 1, respectively.

transferred to and be relaxed at HR because $T_{1\text{eff}}$ is quite short compared to $\tau_1(x_i)$ at IR. $\Delta\rho/\rho|_{\text{ESR}}$ is not observed since most of the absorbed energy is relaxed at HR(II). On the other hand, the Zeeman energy absorbed at LR also tends to flow to HR through IR but, as shown in Fig. 5(a), the energy is relaxed at IR because the thickness of IR is nearly equal to the spin-diffusion length $\{[D_3\tau_1(3)]^{1/2}\}$ at IR for this sample. Here, D_3 and $\tau_1(3)$ are the spin-diffusion coefficient and the mean value of $\tau_1(x_i)$ at IR, respectively (see Table I). Therefore, the $\Delta\rho/\rho|_{\text{ESR}}$ is observed as the broad line which corresponds to the broad ESR signal^{11,12} at LR ($5 \times 10^{17} < N_D \leq 1.5 \times 10^{18}$ P/cm³).

For the ion-implanted Si with 200-keV P and a dose of 3×10^{14} /cm³ (sample No. 2), the block diagram of the relaxation process of the absorbed Zeeman energy is shown in Fig. 5(b). $T_{1\text{eff}}$ is not very short because HR(II) does not exist. Therefore, HR(I) does not cause the Zeeman energy absorbed at IR to flow to and to be relaxed at HR(I). That is, most of the Zeeman energy absorbed at IR and LR is relaxed into the lattice at each region, as shown in Fig. 5(b). Then $\Delta\rho/\rho|_{\text{ESR}}$ is observed as the narrow line which corresponds to the narrow ESR signal of IR and HR(I).^{2-4,11,12}

We now make an estimate of the order of magnitudes for $\Delta\rho/\rho|_{\text{ESR}}$ on the basis of the model. First, we assume for simplicity that each of the four layers [i.e., HR(II), HR(I), IR, and LR] in Fig. 1 contains a constant donor concentration n_i and has a mean value of other physical quantities as shown in Table I. Since resistance changes at LR can be neglected due to $R_4 \gg R_1, R_2$ and R_3 , the resistance change $\Delta\rho/\rho|_{\text{ESR}}$ of the total layers is

$$\begin{aligned} \frac{\Delta\rho}{\rho}|_{\text{ESR}}(\text{calc}) &= \frac{\Delta R_s}{R_s}|_{\text{ESR}} \\ &= \frac{R_2 R_3}{A} \frac{\Delta R_1}{R_1}|_{\text{ESR}} + \frac{R_3 R_1}{A} \frac{\Delta R_2}{R_2}|_{\text{ESR}} + \frac{R_1 R_2}{A} \frac{\Delta R_3}{R_3}|_{\text{ESR}}, \end{aligned} \quad (3)$$

where $R_s^{-1} = R_1^{-1} + R_2^{-1} + R_3^{-1} + R_4^{-1}$, and $A = R_1 R_2 + R_2 R_3 + R_3 R_1$. The resistance change of each layer is

$$\Delta R_1/R_1|_{\text{ESR}} = a_1 P[\text{HR(II)}], \quad (4)$$

$$\Delta R_2/R_2|_{\text{ESR}} = a_2 P[\text{HR(I)}], \quad (5)$$

$$\Delta R_3/R_3|_{\text{ESR}} = a_3 P(\text{IR}), \quad (6)$$

where $P[\text{HR(II)}]$, $P[\text{HR(I)}]$, and $P(\text{IR})$ is the power relaxed at HR(II), HR(I), and IR, respectively, and a_1 , a_2 , and a_3 are the conversion constants ($a_3 > a_2 \gg a_1$).²⁻⁴ The first term in Eq. (3) can be neglected since $\Delta R_1/R_1|_{\text{ESR}} \leq 10^{-10}$.⁴

For sample No. 2, the second and third terms in Eq. (3) are of the same order of 5×10^{-7} and 8×10^{-7} , respectively, if we assume no energy transfer from IR to HR(I). The value of 1.3×10^{-6} is smaller than the observed value of $\Delta\rho/\rho|_{\text{ESR}}$ of 5×10^{-6} . However, this difference seems to be due to the oversimplified approximation of four layers and due to the enhanced diffusion¹⁵ (i.e., l_2 and l_3 become larger).

Assuming that, for sample No. 1, HR(II), HR(I), and IR make one metallic system where there is fast energy

transfer, the ratio of the power, $P'[\text{HR(II)}]$, $P'[\text{HR(I)}]$, and $P'(\text{IR})$, absorbed at each layer and of the power relaxed at each layer is

$$P'[\text{HR(II)}]:P'[\text{HR(I)}]:P'(\text{IR}) = 1:0.88:0.70,$$

$$P[\text{HR(II)}]:P[\text{HR(I)}]:P(\text{IR}) = 1:0.029:0.00083$$

by calculating from Table I. It is found that most of absorbed energy is relaxed at HR(II) and that the second and third terms in Eq. (3) are extremely small. However, the third term in Eq. (3) become dominant due to the energy transfer from LR to IR. We assume that the transferred energies are all relaxed at IR as shown in Fig. 5(a). The power transferred and relaxed at IR is

$$\begin{aligned} P(\text{IR}) &\doteq P'(\text{LR}) \\ &= \frac{\chi_0(4)H_0^2}{\tau_1(4)} \frac{\gamma^2 H_1^2 \tau_1(4) \tau_2(4)}{1 + \gamma^2 H_1^2 \tau_1(4) \tau_2(4)}, \end{aligned} \quad (7)$$

where $\chi_0(4)$ is the paramagnetic susceptibility at LR, γ is the gyromagnetic ratio, $\tau_2(4)$ is the virtual spin-spin relaxation time at LR, H_0 is the static magnetic field at resonance, and H_1 is the oscillating magnetic field. With use of the values in Table I and $\tau_2(4) = 5 \times 10^{-8}$ sec, $H_1 = 0.25$ G, $H_0 = 3200$ G, and $\chi_0(4)$ at 1.6 K = 7.1×10^{-8} cgs/g,¹¹ Eq. (6) is estimated as follows:

$$\begin{aligned} \Delta R_3/R_3|_{\text{ESR}} &= a_3 P'(\text{LR}) \\ &= 8.6 \times 10^{-7} a_3. \end{aligned}$$

Here, $a_3 = (\alpha l_3)/\eta$ in Ref. 3 and we put $\alpha = 1.4$ (cm³/W) and $\eta = 0.25$ at 1.6 K as an averaged value; i.e., $a_3 = 3.5 \times 10^4$ (cm²/W). Therefore, we have

$$\begin{aligned} \Delta\rho/\rho|_{\text{ESR}}(\text{calc}) &\doteq \frac{R_1 R_2}{A} \frac{\Delta R_3}{R_3}|_{\text{ESR}} \\ &= 1.8 \times 10^{-7} \end{aligned}$$

for the broad line of sample No. 1 at 1.6 K. This is smaller than the observed value of $\Delta\rho/\rho|_{\text{ESR}}$ of 7×10^{-7} . However, we think that the agreement on the order of magnitude between the calculation on the basis of the model and experiment is reasonable, in spite of the ambiguity of the value in Table I and that of α .

Finally, we consider that the broad line of $\Delta\rho/\rho|_{\text{ESR}}$ is not due to the bolometric effect,⁵ because the energy relaxed at HR(II) has no effects on $\Delta\rho/\rho|_{\text{ESR}}$, and because the broad line has not been observed in bulk Si:P with much more spins. The broad line is not due to the Q-loss effect⁴ because the linewidth of $\Delta\rho/\rho|_{\text{ESR}}$ does not agree with that of ESR. Furthermore, the narrow line also does not seem to be due to these effects.

V. CONCLUSION

We have observed for the first time the ESR-induced changes in the dc resistance, $\Delta\rho/\rho|_{\text{ESR}}$, of P-ion-implanted Si. A new broad line which cannot be detected by the usual ESR can be detected by this $\Delta\rho/\rho|_{\text{ESR}}$ method. The origin and the mechanism of the new broad line are well explained in terms of the energy-transfer model; i.e., the broad line originates from the ESR of the localized donors at LR and from the transfer of the Zeeman energy absorbed there to IR where the resis-

tance changes take place. The transfer is caused by the existence of HR(II) which acts as a Zeeman energy absorber. This interesting phenomenon has first been observed in the ion-implanted Si:P system but may be expected in other systems which have an impurity distribution within the thin surface layer.

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