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VIII-3. Cyclotron Resonance Study of Electron Scattering by Neutralized Acceptors in Si and Ge

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Electron scattering by neutralized acceptors is extensively investigated for Ge and Si through cyclotron resonance experiments. A simple e^+H scattering picture is certainly a nice guide as in a previous work, but, for some dopants, the observed resonance linewidth does not reflect the genuine scattering relaxation time because of the onset of lifetime broadening. Application of uniaxial stress is helpful to remove this additional broadening.

§ 1. Introduction

Of all the electron scatterings by impurities in semiconductors, that by neutralized acceptors is particularly interesting because of its similarity with the positron-hydrogen scattering. A part of cyclotron resonance study dealing with electron scattering by Ga and In in Ge is already reported.[1,2] One of the special features of acceptor scattering is smallness of cross-section and this suggests a possibility for studying various kinds of acceptor dopants in Si and Ge over a wide range of concentration. Although the positron-hydrogen scattering picture has yielded a success for the treatment of group III impurities in Ge, this approach should be useful only within the framework of the effective mass approximation. For electron scatterings by acceptors other than group III atoms, extension of the effective mass theory is not straightforward, and even for group III atoms, if they are imbedded in Si, situation may be different. Indeed more than trivial difference has been observed in the present work which deals with an extended cyclotron resonance study of impurity scattering. One particular feature is that electron lifetime becomes so short for some acceptors that the resonance line is broadened. This lifetime broadening, however, is lifted by uniaxial stress application and one can find the pure scattering relaxation time under a high stress limit.

§ 2. Cyclotron Resonance with No Stress Application

i) *Si/B, Ga*

Boron is a typical group III impurity in silicon. The inverse relaxation time $1/\tau_B$ for samples with different boron concentrations is given in Fig. 1 against temperature. For comparison, $1/\tau_{In}$ for a particular Ge/In sample is also given. One may note a striking difference in temperature dependence. In a former paper[2] we have seen that a theoretical formula for the e^+H scattering analogue is given by

$$1/\tau_I=3.4N_A(\hbar/m^*)(\hbar^2/2m^*k_B)^{3/2}(12.5T+\hbar^2/2m^*k_Ba^{*2})^{-3/2}a^{*-2}\,. \quad (1)$$

If the effective mass approach is equally good for Si, the only difference should lie in the value of the effective Bohr radius. The group III impurities in Si have deeper energy levels than those in Ge and hence the corresponding Bohr radii are smaller. The effect of temperature in (1) will then be reduced and the observed $1/\tau_I$ should be nearly constant over the temperature interval 1.5—4.2°K. Our experimental observation, however, indicates an entirely different tendency. Moreover, the absolute intensity of

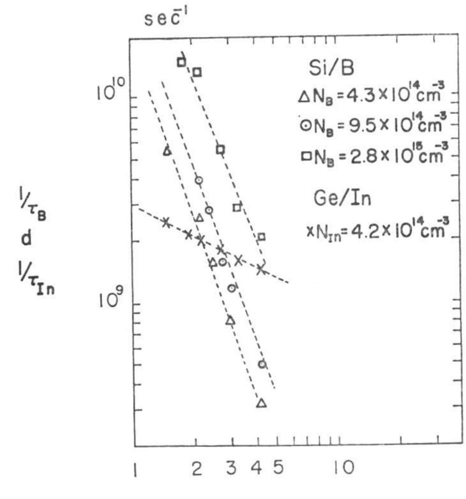

Fig. 1. Inverse relaxation time due to B in Si for three different samples, compared with that due to In in Ge.

resonance signal rapidly goes down with decreasing temperature. The same is true also for Si/Ga.

ii) *Ge/Cu*

General behaviors are more or less the same with group III impurities. Especially the temperature dependence of $1/\tau_{\mathrm{Cu}}$ is almost identical with that of $1/\tau_{\mathrm{In}}$ (Fig. 2). The absolute magnitude of the scattering cross-section for Cu is nearly one-fourth of that for In.

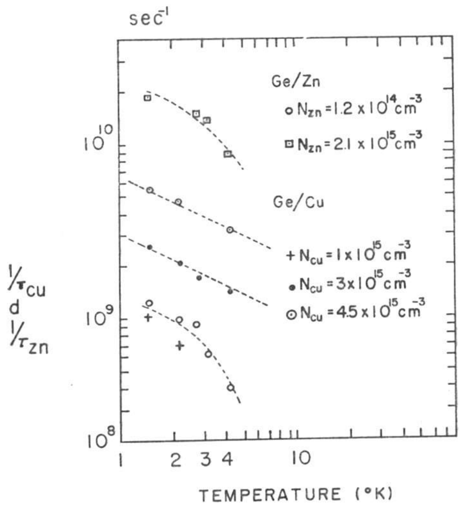

Fig. 2. Inverse relaxation time due to Cu and Zn in Ge.

iii) *Ge/Zn*

We observe a sharp rise of $1/\tau_{\mathrm{Zn}}$ with decreasing temperature, while the intensity of resonance signal goes down. These characteristics are quite similar to those of Si/B. The temperature dependence of $1/\tau_{\mathrm{Zn}}$ is given in Fig. 2.

§ 3. Effect of Uniaxial Compression

In order to see the effect of strain on a scattering center, a uniaxial stress is applied on various kinds of specimens. The stress is applied in the direction ⟨111⟩ for Ge and ⟨100⟩ for Si, thus the energy of the electron valleys along the stress direction is lowered and that of the remaining valleys are raised. Owing to the carrier repopulation, relative intensity of the electron signal for the up-valleys sinks down for increased stress, while that for the down-valleys grows.

i) *Ge/Ga, In*

The down-valley resonance line slightly increases its linewidth on stress application. Since the up-valley resonance lines show no such broadening, the effect should not be ascribed to the change of the impurity state. It is suggested that the electrons transferred to the down-valley via the impurity assisted intervalley scattering retain high electron temperature corresponding to the up-and-down energy difference caused by stress and thus, after thermalization within the electron system, the down-valley resonance will have a broader linewidth. Detailed aspects of this particular effect will be described elsewhere.[3]

ii) *Si/B, Ga*

Despite the similarity of situation with Ge/In, Ga, effect of the stress is entirely different. No such a broadening as mentioned in i) is found, but an overall narrowing as well as increase of the absolute signal intensities is observed in the low temperature range, where the unstressed signal broadens and tends to fade away. In Fig. 3 is given the variation of the signal intensity (linewidth × height) against stress at 2.2°K. It is seen that there is a simple relation

$$I_s = I_0 \exp(\gamma X)\ , \qquad (2)$$

where X is the stress and γ some constant.

We may assume that the observed linewidth consists of three components; lattice scattering $1/\tau_L$, impurity scattering $1/\tau_I$, and lifetime broadening $1/\tau_r$; *i.e.*,

$$1/\tau = 1/\tau_L + 1/\tau_I + 1/\tau_r\ . \qquad (3)$$

The first term $1/\tau_L$ is given by[4]

$$1/\tau_L = 2.9 \times 10^8 T^{3/2}\ , \qquad (4)$$

and can be subtracted forthwith. So we may persue the behavior of $1/\tau_I + 1/\tau_r$ as a function of X at a fixed temperature, say 2.2°K, and this is shown in Fig. 4. If we neglect the hot electron

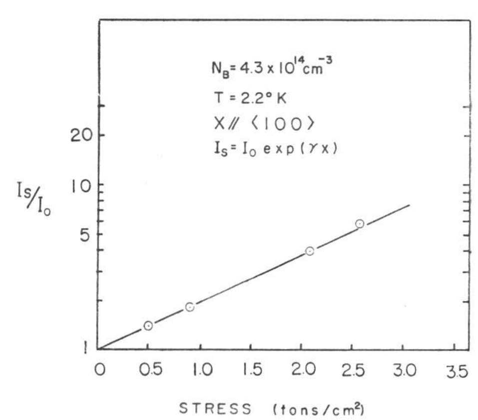

Fig. 3. Change of the total cyclotron resonance signal intensity upon uniaxial stress application.

effect as mentioned in i), $1/\tau_I$ is expected to have no stress dependence and it should simply contribute a constant term, which is only proportional to impurity concentration. It is found that one can describe the behavior by putting

$$1/\tau_I + 1/\tau_r = \beta N_B + (1/\tau_{r0}) \exp(-\gamma' X) . \quad (5)$$

It is interesting to note that γ' derived from Fig. 4 almost perfectly coincides with γ determined from Fig. 3. The fore-factor $1/\tau_{r0}$, which means the inverse lifetime at zero stress, may be written as

$$1/\tau_{r0} = \alpha N_B T^{-n} . \quad (6)$$

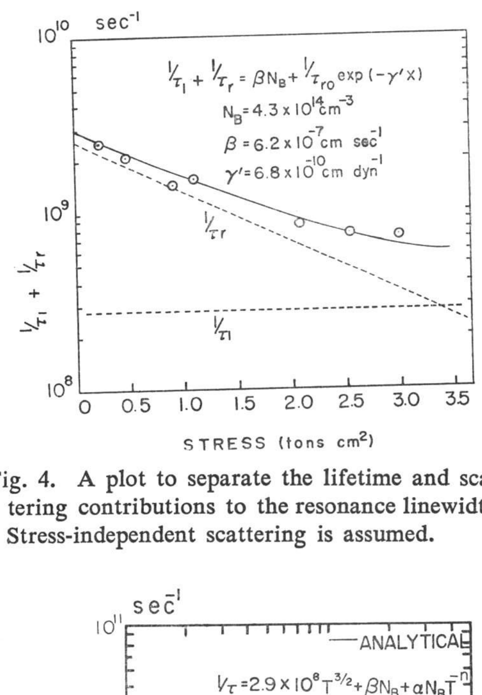

Fig. 4. A plot to separate the lifetime and scattering contributions to the resonance linewidth. Stress-independent scattering is assumed.

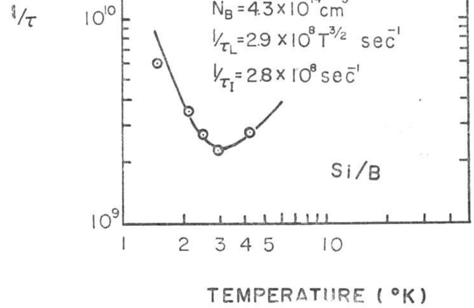

Fig. 5. Comparison of analytical and experimental for Si/B.

Proportionality to N_B is based on the experimental observation and encourages the idea that the majority acceptor itself makes a capturing center for electron. The exponent n to temperature should be found empirically. From these relations and experimental observations, one can derive scattering and lifetime contributions to the observed linewidth and the comparison with the experimental points is made in Fig. 5. Essentially the same results have been obtained for Si/Ga.

iii) *Ge/Zn*

Sensitive reaction to the stress application is similar to the case of Si/B. The $1/\tau_{Zn}$ value at high stress seems to have little temperature dependence and its absolute magnitude is comparable to that of $1/\tau_{Cu}$.

§ 4. Discussions

Determination of pure electron scattering time is sometimes very difficult owing to the onset of lifetime broadening. The apparent sharp rise of $1/\tau_B$ in Si/B, for example, is mostly caused by lifetime broadening. The total $1/\tau_B$ at a fixed temperature, say 2.2°K, is still proportional to the boron concentration and this fact indicates that boron itself is a capturing center for electron. Moreover, the coincidence of γ with γ' implies that boron also makes a recombination center. This situation may be atomistically envisaged as follows: The bound hole cloud around an acceptor is polarized due to the charge of the incident electron. This polarization makes an attractive potential for the electron and thus the electron is temporarily trapped in this polarization trough. One might regard this as an analogue of positronium formation. Before the trapped electron can escape into the conduction band, the electron-hole annihilation, or recombination, takes place and a charged acceptor is left. Then, one of the free hole, which have been excited by illumination, comes across and neutralizes the acceptor, thus restoring its original state. A similar situation must be happening also for Ge/Zn. Conditions for such a process—positronium formation leading to recombination—to occur must certainly be very delicate. The process seems to be operative only at low temperature. Absence of the effect for group III impurities in Ge may be accounted for by assuming that temperature is still too high even at 1.5°K.

§ 5. Conclusions

In some doped crystals, pure electron scattering can be observable only under stress application, and effect of genuine acceptor scattering is always much smaller than that of donor scattering. This is qualitatively accounted for by the positron-hydrogen scattering concept. Its applicability to group I or II acceptors, such as Cu or Zn, cannot be rigorously justified, however. The onset of lifetime broadening certainly obscures the electron scattering. But a detailed study on this separate subject may provide a useful approach for the recombination kinetics. The hot electron effect inherent to the intervalley scattering under the stress application, which is briefly mentioned in i), § 3, also offers a new topic of electron scattering in many-valley semiconductors.

Acknowledgements

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DISCUSSION

Lax, M.: Perhaps you would like to comment further on your evidence for the recombination process.

Otsuka, E.: The fact that you have almost the same slopes between the intensity vs. stress curve and the line-width vs. stress curve suggests a most strong evidence that the line-broadening at low temperatures is caused by recombination rather than trapping.