Memoirs of Fukui University of Technology, Vol. 30, Part 1, 2000

Microwave Studies of Electron-Impurity Scattering in Semiconductors through Cyclotron Resonance

Eizo Otsuka*

Electron cyclotron resonance is studied by microwaves both in n-type and p-type semiconductors. The atomic scattering models for electron and positron have been found very useful in analyzing the electron scattering by neutral donors and neutral acceptors.

Microwave resonance technique has been a powerful tool to lay open the hidden physical properties in various solid materials. Electron paramagnetic resonance of F-center electon in alkali halides heralded the research in this field [1]. The color center, however, is holding an electron in more or less localized state, at most jumping over several ions around the center. The brilliant achievement of cyclotron resonance in germanium and silicon followed only a few years later [2,3]. This new development was to deal with free carriers in semiconductors.

Free carriers ejected into the energy band continuum by band-gap photoexcitation assume harmonic oscillator-like behavior under the application of a magnetic field, giving rise to the so-called Landau levels. Allowed transitions between the Landau levels establish the free carrier cyclotron resonance. The absorption line has a Lorentzian shape, the linewidth of which is inversely proportional to the carrier collision frequency. Carriers are scattered by lattice vibrations, impurities, other carriers, imperfections and so on. Here I will concentrate on the scattering by impurities. The collision frequency $1/\tau$, where τ is the so-called mean free time, is proportional to the impurity concentration N and given by

$$1/\tau = N v \sigma, \tag{1}$$

where v is the velocity of electron and σ the scattering cross section. In thermal equilibrium, v is given by $(3k_B T)^{1/2}$. Meanwhile the cyclotron resonance linewidth ΔB on the magnetic field scale is approximately related to the collision time by the equation

$$\omega_c \tau = 2B_r/\Delta B, \tag{2}$$

where ω_c is the cyclotron frequency, and B_r the resonance magnetic field. Now that the cyclotron frequency can be replaced with the microwave frequency employed, we can derive the collision time.

Actually, the linewidth observed consists of various contributions. In order to derive the collision frequency contributed by impurity scattering, one has to remove other contributions. First, the contribution from lattice vibration or phonon scatterings, can be removed by subtracting the linewidth yielded by extremely pure material. Second, the contribution from carrier-carrier scatteringss can be eliminated by minimizing intensity of the band-gap excitation light. In this way, the electron-impurity scattering contribution to the linewidth can be extracted. Next comes the question of charge state of the impurity. The band-gap illumination creates electron-hole pairs, which promptly neutralize ionized impurities. So what we actually deal with is the electron-neutral impurity scattering.

There exist two kinds of impurities in a semiconductor: donors and acceptors. In silicon and germanium, which are group IV elemental semiconductors, group V impurities

* Department of Electrical Engineering

make donors while group III acceptors. A neutral donor and a neutral acceptor are compared to a hydrogen atom. So electron scattering by a neutral impurity is likely to be treated in terms of electron-hydrogen atom or e^- -- H scattering. That is partly true; or almost exactly true for electron-donor scattering, since the neutral donor consists of a positively charged donor core, which is to be compared to proton, and an electron going around the core. Based on an avialable calculation by Massey-Moiseiwitsch [4], Erginsoy suggested a formula for electron scattering by neutral impurities in semiconductos [5]. Indeed this formula has been known as Erginsoy's formula and widely used in analyzing the contribution of neutral impurity scattering in semiconductors, including experimental results of cyclotron resonance for doped semiconductos. But how about electron-acceptor scattering? On band-gap photoexcitation, all the impurities are neutralized as mentioned above. For a p-type material, one can expect electron scattering by a neutralized acceptor in cyclotron resonance observation. A strong merit of cyclotron resonance is feasibility of separating electron transport and hole transport both in n-type and in p-type materials. The electron cyclotron resonance study in p-type material is just one example. The neutral acceptor in a semiconductor, say neutral Ga in Ge, is something like antihydrogen atom. The negatively charged acceptor core now replaces antiproton and attracts a hole, that replaces a positron. This antihydrogen-like complex is to scatter a conduction electron. Then, if every charge in the scattering process is reversed of its sign, the relevant process becomes something like positron-hydrogen atom scattering, instead of electron-antihydrogen atom scattering. A variational calculation of e^+ -- H has been carried out by Schwartz [6] to give a cross section much smaller than that of e^- -- H scattering. Thus there arises a big difference between electron-donor and electron-acceptor scatterings. Based on the Schwartz calculation, Otsuka *et al.* derived a formula to be employed in the analysis of electron-neutral acceptor scattering in semiconductors [7, 8]. Experimental verification of the situation by 35 GHz cyclotron resonance has been carried out for n-type and p-type germenium crystals and the result is shown in Fig. 1(a). The difference between donor and acceptor scatterings is even more enhanced in doped Si [Fig. 1(b)], where the so-called effective mass approximation is less justified than in doped Ge.

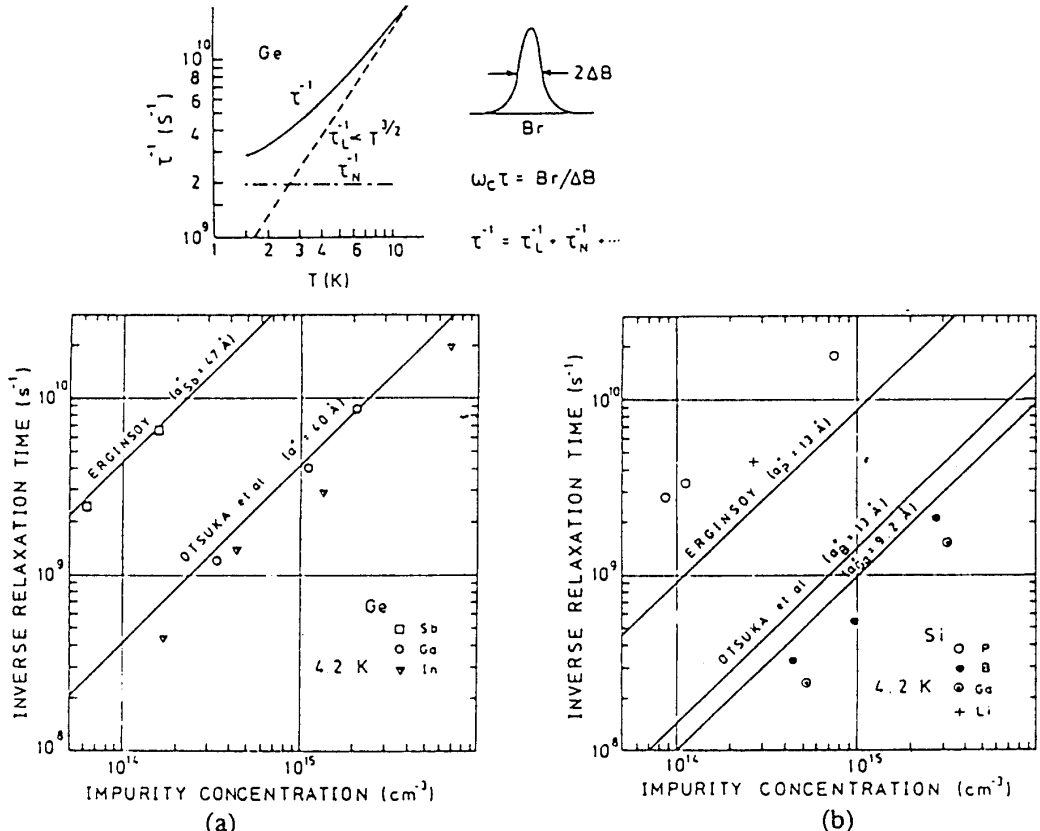
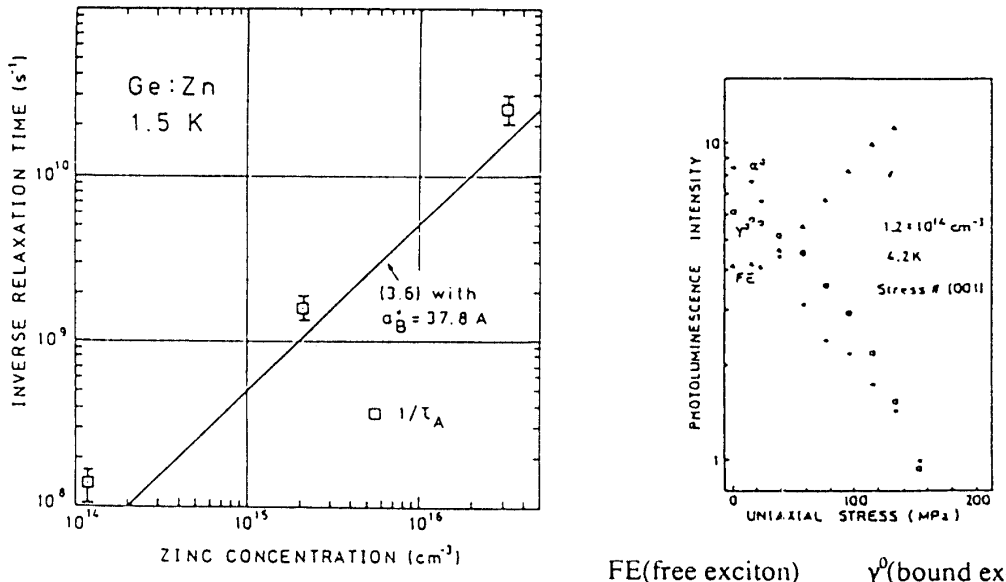


Fig. 1. (a) Inverse relaxation time of electrons at 4.2 K due to neutral impurities in Ge is plotted against impurity concentration. For donors, Erginsoy's prediction is shown by a straight line, while for acceptors, Otsuka *et al.*s prediction, with appropriate Bohr radii.
(b) The same for neutral impurities in Si.
In the above is shown the procedure of deriving the neutral impurity scattering.

So far we described the results for Si and Ge containing only group III and group V impurities. There exist more kinds of donors and acceptors; say, group II or group VI impurities. Zinc in Ge, for example, makes a double acceptor. A neutral zinc impurity in Ge is something like antihelium. Fortunately, there exists a theoretical calculation of e^+ -- He scattering to compare with our experimental observation of electron cyclotron resonance linewidth from Zinc-doped Ge crystals [9]. Surprising enough, the scattering cross section becomes even smaller than the case of a single acceptor. Eventually, we found that the e^+ -- He scattering calculation accounts for our experimental observation very well [Fig. 2]. In the beginning, however, we were not a little puzzled. For the resonance linewidth drastically increases when one lowers temperature, and the signal itself dies down with decreasing temperature. The atomic scattering model never explains such a behavior of electron. Now we understand the behavior quite nicely in terms of exciton formation and its subsequent trapping by neutral zinc impurity. This trapping results in formation of a complex something like a neutral donor. In fact, on capturing an exciton, the impurity center gets three holes and an electron. The three holes then tend to get concentrated around the negatiavely charged zinc impurity, since the acceptor ground state is fourfold degenerate. Then the remaining electron has no other way than orbitting around the positively charged center, which makes a neutral donor-like complex with a large form factor. It is no wonder, accordingly, the Zn-doped Ge sample yields broader and weaker resonance signal at lower temperature.

Another surprise arises when one applies a uniaxial stress on the sample. Even at temperatures lower than 4.2 K, the electron signal suddenly grows up and becomes very slender. The new linewidth is almost completely well accounted for by the above-mentioned atomic scattering model. A quite similar behavior appears in boron-doped Si. Boron, a group III acceptor as it is, has a fairly deep acceptor level in Si, almost as deep as that of zinc in Ge. The neutral boron acceptor easily captures an exciton at low temperature, yielding a donor-like complex again here. Thus we can jointly explain the singular behavior in Zn-doped Ge and B-doped Si. Indeed, independent optical measurements have justified the interpretation of electron cyclotron resonance behavior in terms of exciton trapping by neutral acceptors, by observing the intensities as well as photon energies of free excitons and bound excitons as a function of applied uniaxial stress. As one increases the stress, the intensity of free exciton luminescence also increases, indicating the release of bound excitons. The difference in photon energy between bound and free excitons decreases with stress. That means decrease in binding energy of bound excitons, leading to release of excitons. Since the free carrier density should increase with increasing free exciton density, the growth of electron cyclotron resonance intensity with uniaxial stress is quite easy to understand.



FE(free exciton) γ^0(bound exciton)

Fig. 2. Inverse relaxation time of electrons due to neutral Zn acceptors in Ge against Zn concentration. The data were obtained at 1.5 K using 35 GHz waves, after eliminating the bound exciton effect by applying a strong uniaxial stress. The straight line is drawn after the theoretical positron-helium atom scattering model.

The size difference between donor- and acceptor-scatterings is further enhanced when one deals with III-V compound semiconductors. Typical feature is shown in Fig. 3 for electron cyclotron resonance in a pair of n- and p-type GaAs samples containing nearly the same amount of impurities [10]. For dealing with cyclotron resonance in III-V semiconductors, millimeter waves can do very little. Here we employed a wavelength of 172 μm.

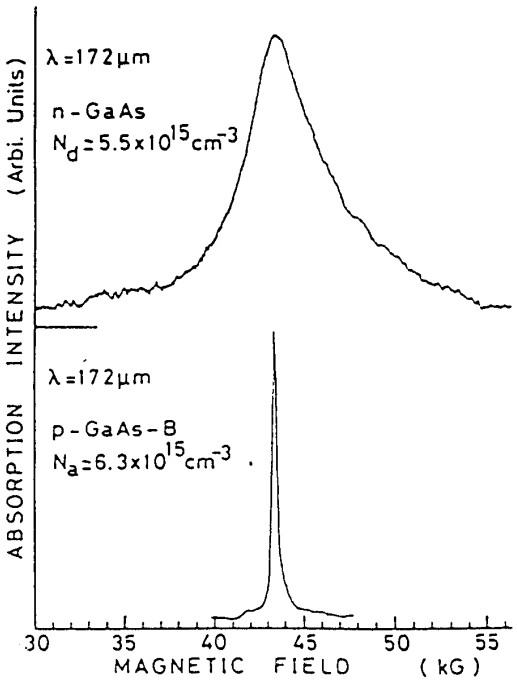


Fig. 3. Cyclotron resonance traces obtained from n- and p-type GaAs samples having the same order neutral impurity concentrations. The data were taken at 4.2 K with a wavelength of 172 μm.

In this paper we have presented some usage of microwaves for studying electron cyclotron resonance in semiconductors. The crop is certainly enormous. But one should always keep it in mind, that the microwaves can lay open only one face of materials science. Only with combination of optical method as well as extended use of wavelength, one can grasp the whole feature of physics in materials science.

REFERENCES

[1] A. F. Kip, C. Kittel , F. A. Levy and A. M. Portis: Phys. Rev. 91 (1953) 1066.
[2] B. Lax, H. J. Zeiger and R. N. Dexter: Physica 20 (1954) 818.
[3] G. Dresselhaus, A. F. Kip and C. Kittel: Phys. Rev. 98 (1955) 368.
[4] M. S. M. Massay and B. L. Moiseiwitsch: Phys. Rev. 78 (1950) 180.
[5] C. Erginsoy: Phys. Rev. 79 (1950) 1913.
[6] C. Schwartz: Phys. Rev. 124 (1961) 1468.
[7] E. Otsuka, K. Murase and J. Iseki: J. Phys. Soc. Jpn. 21 (1966) 1104. See also [8].
[8] E. Otsuka: Jpn. J. Appl. Phys. 25 (1986) 303.
[9] N. R. Kestner, J.J. Morrel, M. H. Cohen and A. R. Stuart: Phys. Rev. A140 (1965) 56.
[10] H. Kobori, T. Ohyama and E. Otsuka: Solid State Commun. 63 (1987) 123.

(Received December 8 , 1999)