PROC. 15TH INT. CONF. PHYSICS OF SEMICONDUCTORS, KYOTO, 1980
J. PHYS. SOC. JAPAN 49 (1980) SUPPL. A p. 461–464

DYNAMICAL BEHAVIOUR OF EXCITON SYSTEM IN SILICON

Tyuzi Ohyama

Department of Physics, College of General Education,
Osaka University, Toyonaka, Osaka, Japan

We report on the first observation of the far-infrared(84-220 μm) laser magneto-absorption by the excitonic system in silicon. The major absorption lines are safely attributed to the 1s → 2p type Zeeman transition of excitons. It is found that the absorption line-width is sensitive to temperature and to impurity concentration. The work function of the condensed phase is obtained through the thermodynamical method to be ψ=7.6meV.

I. Introduction

A large number of experiments [1] on the high density exciton system in germanium have been performed. The far-infrared laser magneto-absorption [2], in particular, has been used to make a direct observation of the dynamical properties of excitons. No comparable experiment exists for silicon. The main probe to investigate the excitonic system in silicon has so far been restricted only to recombination spectra [1]. Some practical information is the band edge absorption provided by Shaklee and Nahory [3] who gave the 1s to 2p separation to be 10.7meV and 11.0meV for TA and LA phonon assisted transitions, respectively. These energies correspond to the far-infrared region around the wavelength of 100 μm. In the absence of a magnetic field, moreover, Timusk et al. [4] have recently furnished new experimental information of the 1s → 2p type transitions of excitons in silicon.

In this work we report on the first observation of the far-infrared laser magneto-absorption of excitons in silicon, which leads to some important conclusions about their dynamical properties.

II. Experimental

Experiments are performed on an undoped(N_A-$N_D \simeq 10^{12}cm^{-3}$), three boron-doped($N_B$=$8.0\times10^{13}cm^{-3}$, N_B=$4.3\times10^{14}cm^{-3}$, N_B=$2.0\times10^{15}cm^{-3}$) and two phosphorous-doped(N_P=$8.8\times10^{13}cm^{-3}$, N_P=$8.0\times10^{14}cm^{-3}$) silicon crystals. The wavelengths of 84-220 μm are obtained from both an H_2O laser and an optically pumped laser, and operated in pulses in synchronized combination with the photoexcitation. The excitation light is provided by a xenon flash lamp having the pulse width of ∿1 μs and operated at 15 Hz. Temperature is varied between 1.7 and 50 K. Other details are the same as described elsewhere [2].

III. Zeeman Effect of Excitons

Figure (1) shows the typical spectra from the undoped sample observed at 4.2 K for several wavelengths and at the geometry of B //

<111>. The major absorption lines show a little anisotropy and the positions strongly depend on the wavelength of the laser. Moreover, the Zeeman absorption lines can be observed only in the limited region of wavelength. For example, we have no absorption signal for 146 μm(8.5meV), which shows that the first excited state exists at energy higher than 8.5meV. For 84 μm(14.8meV), a non-resonant absorption is observed, which originates in the photo-ionization of excitons into free pairs.

Button et al. [5] introduced a phenomenological Zeeman energy of the form

$$E = a_J + b_{SJ}B + cB^2 \quad ; \tag{1}$$

where the first term represents the zero-field splitting, the second represents the usual Zeeman energy depending on the total angular momentum S, J of electrons and holes, respectively, and the third represents an isotropic diamagnetic contribution. The values of the coefficients obtained by fitting our experimental data for B // <111> with the above formula are $b_{SJ}=(\pm 1.4 \times 10^{-2}$meV/kG, $\pm 0.39 \times 10^{-2}$meV/kG, 0.09×10^{-2}meV/kG) and $c= 3.63 \times 10^{-4}$meV/(kG)^2.

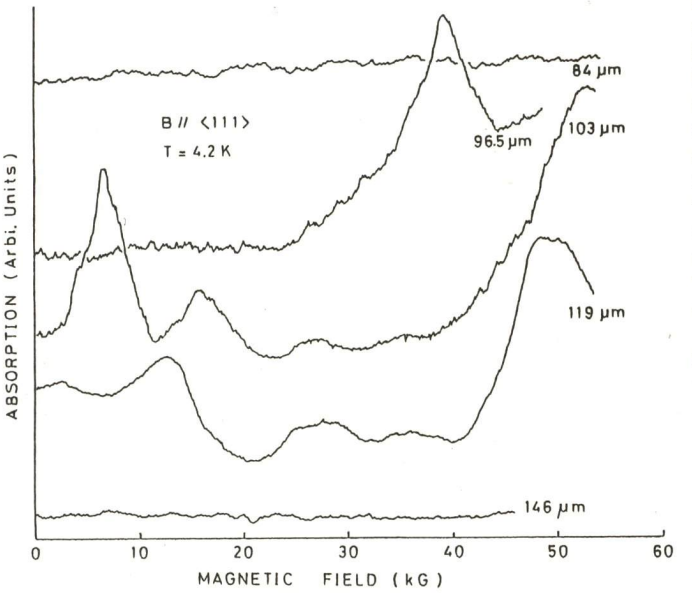

Fig. 1 Magneto-absorption traces from an undoped Si for various wavelengths at the geometry of B // <111>

IV. Line-width of Exciton Zeeman Absorption

The exciton will have a fairly short lifetime against scatterings which affect the line-width of the far-infrared Zeeman absorption for excitons. It should be noted that the scattering may occur both by phonons and by impurities. The line-width ΔB of the absorption has been studied as a function of temperature and concentration of impurities.

The temperature dependence of the half-width ΔB for the undoped sample obtained for the wavelength of 119 μm and for B // <001> is shown in Fig.(2) in logarithmic scales. It should be noted that the half-width increases roughly linearly with the temperature above 5 K. Below 5 K, it tends to be independent of temperature. The linear dependence of the half-width on temperature confirms Toyozawa's theory [6] and indicates that the broadening of the excitonic absorption line for the undoped silicon is due mainly to the exciton-phonon interaction. Most noticeable is the decrease of temperature

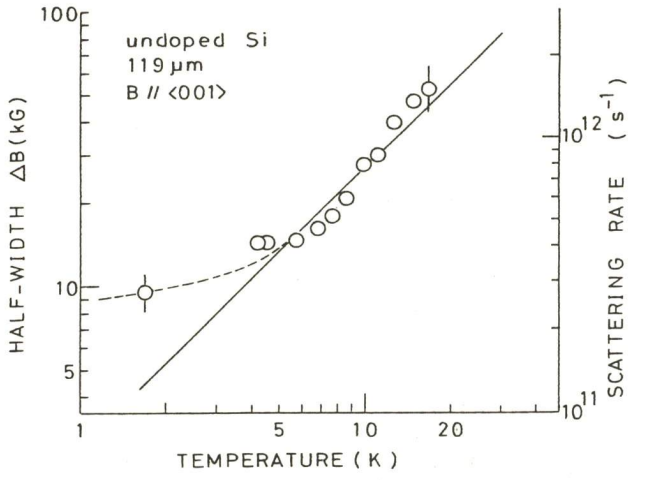

Fig. 2 Temperature dependence of the half-width of the excitonic Zeeman absorption line for the undoped silicon: The same data give the scattering rate (see the scale on the right). The solid straight line having the slope of 45° indicates the linear dependence of the scattering rate on temperature.

dependence of the half-width below 5 K. This phenomenon, which also follows from the theory, indicates that at low temperatures the scattering rate of excitons is mainly determined by their interaction with the zero point lattice vibrations.

We have further looked for a correlation between the half-width ΔB_I and the impurity concentration. The genuine contribution of impurities to the line-width, can be obtained after subtracting the effect of phonon scatterings. The proportionality of ΔB_I to N_B and to N_P shows that the observed effect really reflects the scattering by doped impurities. The cross section of the exciton-impurity scattering does not depend on the type of dopant, i.e., either donor or acceptor. Recently Elkomoss and Nikitine [7] have calculated the exciton-neutral impurity elastic collision cross section, based on the perturbation theory by the interaction of the Van der Waals type. They predict that the cross section depends only on the Bohr radius of the impurity and on the velocity, Bohr radius, etc. of excitons. Since the Bohr radius is nearly the same for donor and acceptor, it is not too surprising that the scattering cross section apparently does not depend on the type of impurity.

V. Thermodynamical Determination of Work-function for Electron-Hole Drop

The excitonic absorption behaviour strongly depends both on temperature and on excitation level. That is a characteristic feature of excitons coexisting with electron-hole drops. Figure (3) shows the dependence of the absorption coefficient, obtained at the wavelength of 119 μm and at B=0, on the reciprocal temperature at different excitation levels. Starting with a certain threshold temperature T_{th}, the absorption decreases sharply. The FIR absorption being proportional to the exciton concentration, the straight line drawn through the threshold points, indicated with cross mark, separates the diagram into two parts: one corresponding to the region in which the exciton system is in the gas phase while the other to the liquid and gas coexisting phase. Based on the simple model for the coexisting system, the boundary line is expressed as

$$g_{th} = (4A/v_{ex}\tau_{ex})\exp(-\psi/kT_{th}) \quad . \tag{2}$$

Here v_{ex} and τ_{ex} are the average thermal velocity and the lifetime of excitons, respectively, A the coefficient inherent to the thermoionic

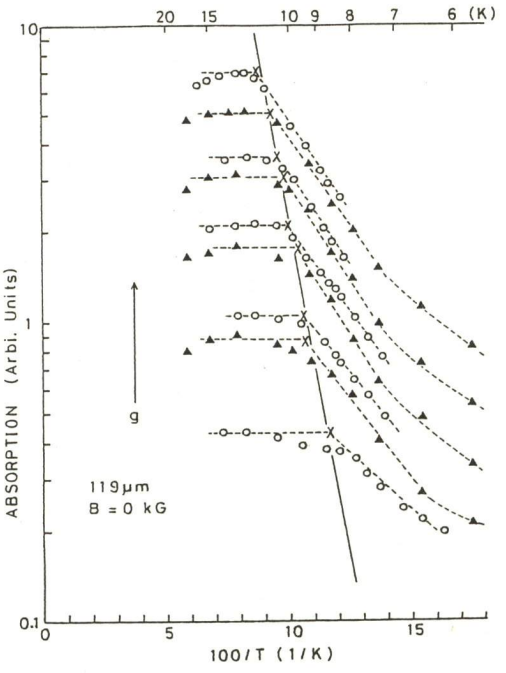

Fig. 3 Temperature dependence of the excitonic absorption intensity at different excitation levels g. Crosses represent the threshold points derived from our measurements. The solid straight line drawn through the crosses yields the value of the work function ψ=7.6meV according to eq. (2) (see text).

emission and ψ the work function. The solid line in Fig.(3) corresponds to eq. (2) with ψ=7.6meV. To our knowledge, this is the first determination of the work function for electron-hole drop in silicon through the thermodynamical method.

We further conclude that a plasma composed of free carriers in thermal equilibrium with excitons exists above 15 K, through the parallel measurements of the far-infrared absorption for 220 μm (free carriers) and 119 μm(excitons). Both systems can be explained well by a chemical equilibrium between free carriers and excitons with the binding energy E_{ex}=14.7meV. From the time-resolved experiments we have obtained the temperature dependence of the lifetime of excitons. At higher temperatures, it seems that we have two time constants for exciton decay. The initial fast decay may be due to the Auger recombination among excitons and the subsequent slower decay, which depends on temperature, is considered to originate in the recombination via impurities. It is found that this slow decay constant reaches 30 μs above 20 K.

The author expresses his thanks to Prof. E. Otsuka and to his colleague H. Nakata for useful discussions.

References

1) J.C. Hensel, T.G. Phillips and G.K. Thomas: Solid State Physics, ed. H. Ehrenreich, F. Seitz and D. Turnbull (Academic Press, New York and London, 1977) Vol. 32, p.87.
2) E. Otsuka, T. Ohyama, H. Nakata and Y. Okada: J. Opt. Soc. Am. 67 (1977) 931.
3) K.L. Shaklee and R.E. Nahory: Phys. Rev. Letters 24 (1970) 942.
4) T. Timusk, H. Navarro, N.O. Lipari and M. Altarelli: Solid State Commun. 25 (1978) 217.
5) K.J. Button, L.M. Roth, W.H. Kleiner, S. Zwerdling and B. Lax: Phys. Rev. Letters 2 (1959) 171.
6) Y. Toyozawa: Progr. Theor. Phys. 20 (1958) 53.
7) S.G. Elkomoss and S. Nikitine: J. Phys. Chem. Solids 41 (1980) 413.