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Off-equilibrium population of holes in the stress-split valence bands in photoexcited silicon and germanium

A. Uddin, H. Nakata, and E. Otsuka
Department of Physics, College of General Education, Osaka University, 1-1 Machikaneyama-cho, Toyonaka-shi, Osaka 560, Japan
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Uniaxial-stress effects on exciton systems are investigated by use of photoluminescence measurements in pure Si and Ge at low temperatures. The excitation intensity ranges from mW to MW levels. We observe an off-equilibrium population of light holes in the stress-split valence band in Si under high excitation as well as that in Ge at 200 mW under uniaxial stress. The population of light-hole-related hot excitons is enhanced and their lifetime decreases with increasing stress both in Si and in Ge; the free-exciton luminescence intensity decreases exponentially with increasing stress under low excitation. Possible mechanisms are suggested for explaining the stress-associated light-hole population and the decrease of the free-exciton luminescence intensity.

I. INTRODUCTION

Over the years the effect of uniaxial stress on semiconductors has been studied by observing changes in the optical absorption or emission spectra. Most of the work dealt with indirect-band-gap semiconductors, mainly Si and Ge. Indeed one can find many articles on the behavior of electron-hole liquid (EHL) under uniaxial stress in Si and Ge,[1-8] but still very little is known about the effect of stress on free-exciton (FE) system in Si and Ge. So our aim is to investigate carefully the behavior of FE under uniaxial stress in pure Si and Ge under different excitation intensities by photoluminescence (PL) measurements at low temperatures.

We find very interesting behavior of FE both in Si and in Ge. A hitherto unknown PL peak arises in uniaxially stressed pure Si under extremely high excitation by use of a pulsed dye laser of MW power in time-resolved measurements. The peak splits up to the higher-energy side from the FE peak (TO- and/or LO-phonon replica) with stress. This observed splitting is comparable to the splitting of the valence bands in Si under uniaxial stress. So we suggest that this peak may be due to exciton recombination involving hot holes. The peak intensity becomes stronger with increasing stress while the peak duration time decreases. Meanwhile, under low excitation intensity the FE peak intensity decreases with increasing stress. Similar types of phenomena are observed also in pure Ge, but under somewhat different experimental conditions. Excitation is made by a cw Ar^+ laser with as low a power as 200 mW. The FE (LA phonon) line splits into three peaks under stress. The light-hole-related hot-exciton emission line becomes stronger with increasing stress in comparison with the other two peaks. The lifetime of hot excitons also decreases with increasing stress in Ge. Stress-associated enhancement of light holes, in a sense similar to our case, has been observed by other authors[9-12] in the presence of crossed electric and magnetic fields. In highly excited GaAs, GaSb, and Si, Auger-excited holes in the split-off valence band have also been observed by other authors at low temperatures.[13-15] Our observation also suggests that, in indirect-band-gap semiconductors, the population of light holes in the stress-split valence band may be due to exciton-exciton scattering or exciton-exciton Auger process.

We have further examined the effect of stress on the luminescence intensity of FE and EHL at a low excitation of 200 mW. The EHL is very unstable under homogeneous uniaxial stress both in Si and in Ge. Free-exciton luminescence intensity in Si and Ge exponentially decreases with increasing stress. The kinetics of this decrease is not so clear. We offer some probable reasons, which we had briefly presented in an earlier report.[16] In the present paper we are trying to give a more precise explanation of this interpretation. We begin by describing a brief experimental outline in Sec. II. The change in band structure and its effect on excitons under uniaxial stress are explained in Secs. III and IV. Finally we summarize our conclusions in Sec. V.

II. EXPERIMENTAL

Specimens used for the experiment were pure Si and Ge single crystals. Silicon was grown by the float-zone method. The sample was carefully polished by diamond paste and slightly etched in CP4 solution to reduce the surface recombination velocity of carriers before mounting. The sample dimensions were $1\times1\times3.5$ mm^3 of Si and $1\times1\times2.5$ mm^3 of Ge. The uniaxial stress was applied along the $\langle 100 \rangle$ direction for Si and the $\langle 111 \rangle$ direction for Ge. For stationary measurements the sample was excited by an Ar^+ laser of 200 mW power at $\lambda = 514.5$ nm and the incident power was kept constant throughout the experiment. The Ar^+ laser beam was mechanically chopped at 200 Hz. The photoluminescence measurements were performed on Si at 2 K and on Ge at 2 and 4.2 K. In Si, at 2 K we observed FE (TO/LO phonon replica) and EHL (TO- and/or LO-phonon repli-

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ca) peaks as well as three bound-exciton peaks at zero stress. The EHL peak and the bound-exciton peaks were very sensitive to stress. Bound-exciton peaks totally disappeared at 22 MPa stress while the EHL peak disappeared at 157-MPa stress. Disappearance of the EHL peak was due to a decrease in binding energy of EHL with stress in Si. In Ge at 2 K we observed strong EHL (LA phonon) and weak FE(LA phonon) peaks. At 4.2 K, on the other hand, we saw strong FE(LA) peak and weak EHL(LA) peak which are very sensitive to stress. The EHL peak apparently disappeared at ~10-MPa stress. So it is very convenient to study the effect of uniaxial stress on the FE(LA) line at 4.2 K.

The PL signal was analyzed by a high-resolution monochromator and was detected by a Ge *p-i-n* photodiode, cooled to 77 K, with a response time of 0.2 μs. The detected signal was recorded through a conventional lock-in amplifier. The impurity concentration in Si was calculated by PL measurements, using the method of Tajima,[17] to yield 3×10^{11} cm^{-3} (boron). The impurity concentration in Ge was $\sim10^{12}$ cm^{-3}. For time-resolved measurements, the Si sample was excited by a pulsed dye laser of a power of 5 MW at $\lambda=590$ nm with a pulse width of 10 ns. The decay of luminescence intensity was measured by the gate scanning of a boxcar integrator. Stress homogeneity was checked by Ar^+-laser PL measurements of the FE luminescence. No broadening of the exciton peak was observed with stress. Stress homogeneity was also checked by time-resolved measurements of the FE luminescence. No change of the exciton peak position was observed for different delay times. These indicated highly homogeneous stress conditions on our samples. Throughout the investigation the samples were in the same setting.

III. THE BAND STRUCTURE UNDER UNIAXIAL STRESS

The application of a uniaxial stress in indirect-band-gap semiconductors removes the degeneracy of the $J=\frac{3}{2}$ valence-band states and that of the many-valley conduction-band states. The splitting of these states due to the strain-orbit interaction can be described by two independent deformation potentials.[18] Theoretical as well as experimental works are available for the definition of the effective masses and the deformation potentials at the band extrema.[19] The typical analysis techniques include excitonic recombination luminescence and cyclotron resonance, all of which have been studied successfully under uniaxial stress.

The present studies have been made on pure Si and Ge with effective uniaxial stress along the ⟨100⟩ and ⟨111⟩ directions, respectively. Stress on Si along the ⟨100⟩ direction decreases the conduction- and valence-band degeneracies. One then obtains a system, frequently denoted by Si(2;1), where the numbers in the parentheses give the conduction- and valence-band degeneracies.[20] The unstressed case is denoted by Si(6;2). Similarly, stress on Ge along the ⟨111⟩ direction yields a system denoted by Ge(1;1). The unstressed case is denoted by Ge(4;2).[21]

A. Stress parallel to the ⟨100⟩ direction in silicon

In Si, we have investigated the effect of uniaxial stress on the band structure as well as the population of excitons associated with different bands by observing the PL spectra. Figure 1 shows the measured PL spectra by Ar^+-laser excitation as well as by dye laser excitation. In Ar^+-laser excitation measurements (spectrum *a*) at zero stress we observe FE(TO/LO), EHL(TO/LO), and three bound-exciton peaks which are very sensitive to stress. On application of stress, two new peaks of hot free excitons (hFE) with TO and LO phonons come out on the higher-energy side of the FE(TO/LO) peak, and the EHL(TO/LO) peak gradually disappears. The hFE peak is due to the recombination of the "hot" electron from the upper four conduction valleys and the heavy hole from $m_j=\pm\frac{1}{2}$ level of the valence band as shown in Fig. 2. The FE(TO/LO) peak is related with the "cold" electron from the lower two conduction valleys and the heavy hole.

In time-resolved measurements we have observed a new peak "*S*" under high excitation as shown in Fig. 1, which appears on the higher-energy side of the FE(TO/LO) peak on application of stress. The intensity of the *S* peak becomes stronger and the splitting of this peak from the FE(TO/LO) peak becomes larger with stress. We suggest that this *S* peak may be exciton luminescence related with the cold electron from the lower two conduction valleys and the light hole from the $m_j=\pm\frac{3}{2}$ level of the stress-split valence band, since its en-

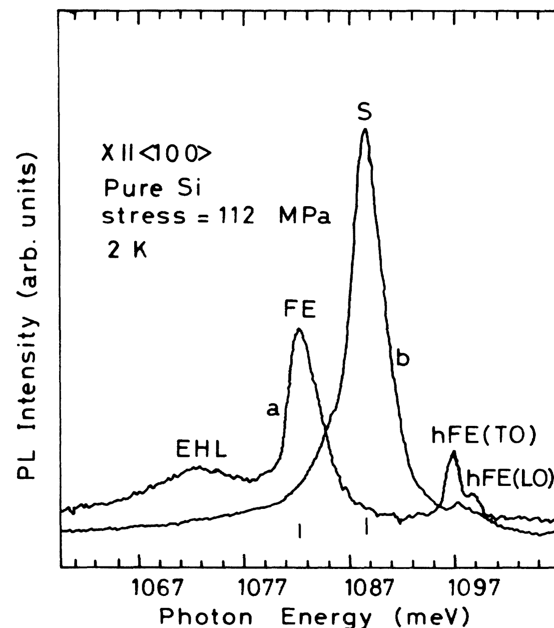

FIG. 1. Photoluminescence spectra at 2 K of phonon-assisted recombination of free excitons in pure Si under uniaxial stress. The spectrum *a* is after cw Ar^+-laser excitation, while the spectrum *b* is from the time-resolved measurement at high excitation by a pulsed dye laser.

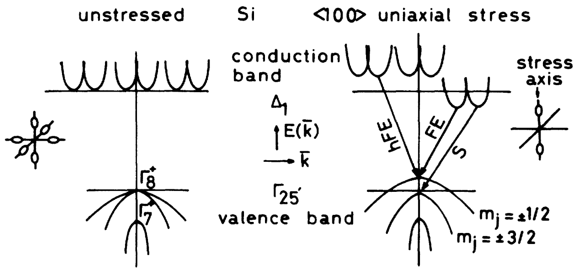

FIG. 2. The schematic diagram of the band structure in Si. The observed transitions under stress are indicated by arrow heads.

ergy separation from the FE peak is comparable with the stress-split valence band as shown in Fig. 2. The splitting of different peaks with uniaxial stress from zero stress are shown in Fig. 3. The hFE peak energy almost remains constant with stress. The peak energy difference between the FE(TO/LO) and the EHL(TO/LO) decreases with stress. It means that the binding energy of EHL is decreasing with stress.

The splitting of conduction-band valleys is measured from the energy difference between the FE(TO/LO) peak and the hFE(TO) peak with stress by neglecting the effect of decrease in excitonic binding energy. Experimentally we have found a relation between the intervalley splitting and the uniaxial stress as

$$\Delta E_{cv} = 0.121X[\mathrm{MPa}]\ \mathrm{meV}\ , \tag{1}$$

where X is in units of MPa. We have also calculated the corresponding shear deformation potential Ξ_u from our experimental data. It is found to be 11.2 eV by using the relation[22]

$$\Delta E_{cv} = \Xi_u (s_{11} - s_{12}) X\ , \tag{2}$$

where s_{11} and s_{12} are elastic compliance constants. We take $s_{11} - s_{12} = 1.076 \times 10^{-5}\ \mathrm{MPa}^{-1}$ (Ref. 23). The splitting of light- and heavy-hole valence bands is measured from the energy difference of the FE(TO/LO) peak and the "S" peak under stress, again by neglecting the effect of the exciton's binding energy decrease. This splitting is related to the stress by

$$\Delta E_{\mathrm{VB}} = 0.053X[\mathrm{MPa}]\ \mathrm{meV}\ , \tag{3}$$

where X is again given in units of MPa. The shear deformation potential of the valence band D_u is found to be 4.9 eV by using the relation[24]

$$\Delta E_{\mathrm{VB}} = \tfrac{4}{3} D_u (s_{11} - s_{12}) X\ . \tag{4}$$

Our measured shear deformation potential of the conduction band is slightly different from other authors' values (Refs. 22 and 24).

B. Stress parallel to the ⟨111⟩ direction in germanium

The uniaxial stress along the ⟨111⟩ direction is more sensitive to the Ge band structure than other directions. The PL intensity of FE(LA) is stronger in Ge than that of other phonon-associated peaks. So we mainly investigate the behavior of the FE(LA) peak with uniaxial stress. The band structure of Ge is more sensitive than that of Si to uniaxial stress. We find that the FE(LA) peak splits into three peaks with uniaxial stress as shown in Fig. 4.

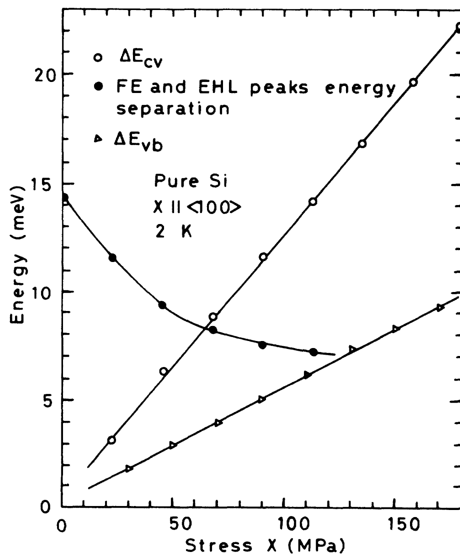

FIG. 3. The splitting of the conduction-band valleys, light- and heavy-hole valence bands, and the change in binding energy of EHL are plotted at 2 K as a function of stress in Si from our observed data.

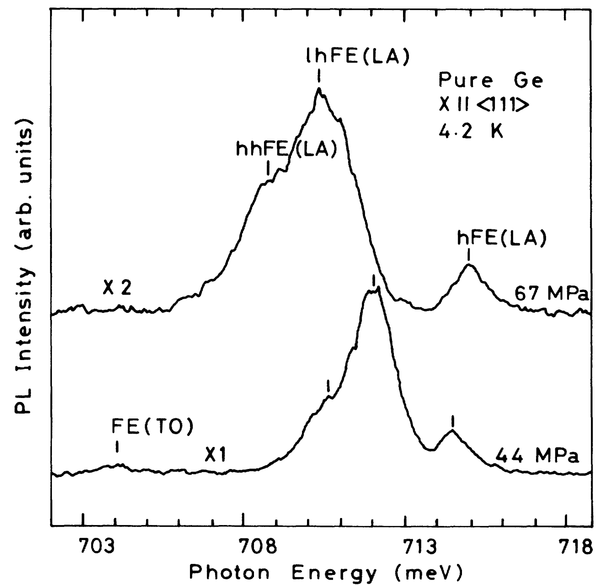

FIG. 4. Photoluminescence spectra at 4.2 K of FE(LA) in pure Ge under uniaxial stress. The FE(LA) line at zero stress is split into three peaks, hhFE(LA), lhFE(LA), and hFE(LA), on application of stress (see text).

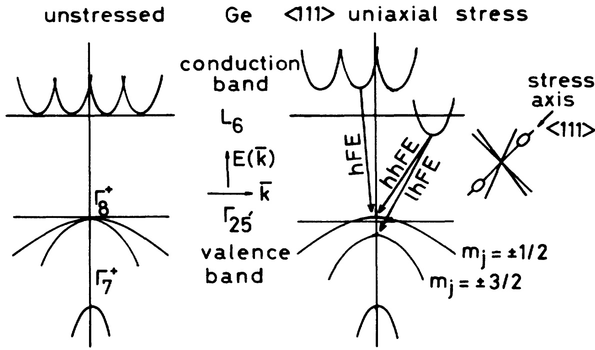

FIG. 5. The schematic diagram of the band structure in Ge. The observed transitions under stress are shown by arrow heads.

The higher-energy peak hFE(LA) is due to the recombination of the free exciton, which consists of the "hot" electron from the upper three valleys of the conduction band and the heavy hole from the $m_j = \pm\frac{1}{2}$ level of the valence band. The middle and strongest peak lhFE(LA) is related with the "cold" electron from the lower valley of the conduction band and the light hole from the $m_j = \pm\frac{3}{2}$ level of the valence band. This peak is a type similar to peak S in Si. The lower-energy peak hhFE(LA) is due to the recombination of the free exciton made up from the "cold" electron and the heavy hole. All of the three peaks are shown in Fig. 5 in the form of electronic transition within the band structure of Ge under uniaxial stress, neglecting excitonic binding energy.

By Ar^+-laser measurements at zero stress we also observe the EHL(LA) line. The EHL line is very sensitive to homogeneous stress. At around 10-MPa stress, the EHL(LA) peak totally disappears. The peak energies of the split three peaks of FE(LA) are shown in Fig. 6. We have measured the splitting of conduction-band valleys from the energy separation of hFE(LA) and hhFE(LA) lines with uniaxial stress. The energy separation of lhFE(LA) and hhFE(LA) lines gives the splitting of heavy- and light-hole valence bands with stress as shown in Fig. 7, if the stress dependence of exciton binding energy is the same for lhFE(LA) and hhFE(LA). The shifting of the energy gap, ΔE_g, is measured from the energy separation between the FE(LA) peak under stress and the FE(LA) peak at zero stress. The intervalley splitting, the valence-band splitting, and the shifting of the energy gap are measured with uniaxial stress. The resultant relations are

$$\Delta E_{cv} = 0.115X[\text{MPa}]\ \text{meV} + C\ , \qquad (5)$$

$$\Delta E_{\text{VB}} = 0.027X[\text{MPa}]\ \text{meV}\ , \qquad (6)$$

and

$$\Delta E_g = 0.093X[\text{MPa}]\ \text{meV} + C\ , \qquad (7)$$

where C is a constant. From the slope of ΔE_{cv} and ΔE_{VB} versus X, we have also calculated the shear deformation potential of the conduction band to be $\Xi_u = 17.7$ eV and the valence band to be $D_u = 2.7$ eV from our observed data, by using the expressions:[25,26]

$$\Delta E_{cv} = \tfrac{4}{9}\Xi_u s_{44} X + C \qquad (8)$$

and

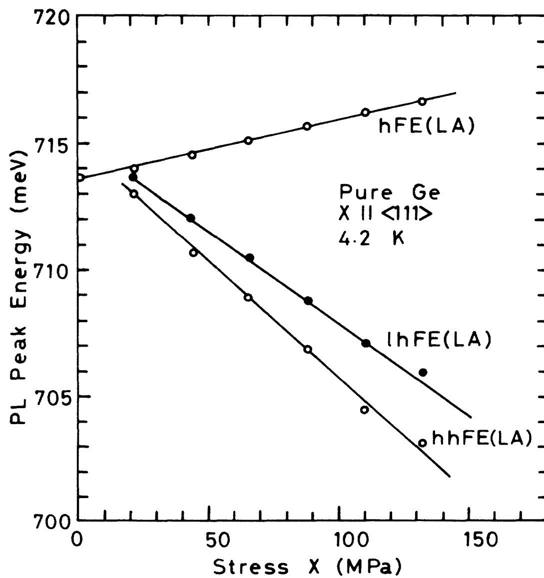

FIG. 6. In Ge the splitting energies of the three peaks from the FE(LA) peak are plotted at 4.2 K as a function of stress in Ge.

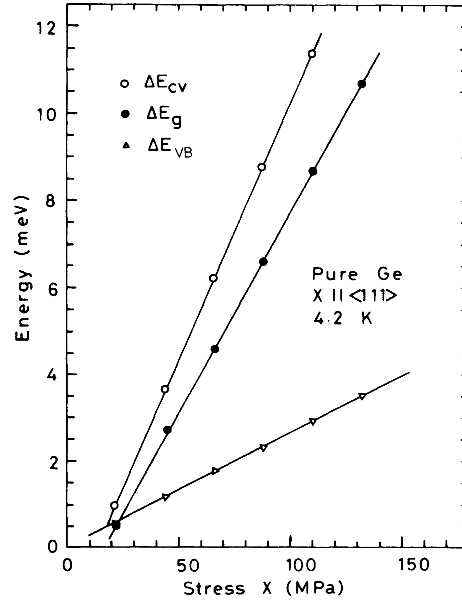

FIG. 7. In Ge the splitting of the conduction-band valleys, that of light- and heavy-hole valence bands, and the shifting of energy gap E_g are plotted at 4.2 K as a function of stress along ⟨111⟩.

$$\Delta E_{VB} = \tfrac{2}{3} D_u s_{44} X , \quad (9)$$

where $s_{44} = 1.458 \times 10^{-5}$ MPa^{-1} (Ref. 25), the inverse of the shear modulus. Allowing for the difference in experimental procedures, the derived deformation potentials give a reasonable agreement with other authors' values (Refs. 22 and 25–27).

IV. EXCITONS UNDER UNIAXIAL STRESS

In indirect-band-gap semiconductors, the phonon-assisted recombination of excitons can be observed by PL measurements. By observing the excitonic luminescence, we can accurately study the behavior of the Γ_{25} valence-band maxima and the Δ_1 conduction-band minima under stress in Si. We have measured the FE(TO/LO) and EHL(TO/LO) peak intensity in Ar^+-laser excitation with stress in Si as shown in Fig. 8. The FE peak intensity becomes stronger with stress, giving a maximum at 55 MPa. This may be due to the evaporation of excitons from EHL. Wagner *et al.*[28] suggest that the decay of EHL in a uniaxially ⟨100⟩ stressed Si is governed by the evaporation of free excitons because of the sharp reduction in binding energy of EHL. After 55 MPa the FE peak intensity nearly exponentially decreases. It tends, however, to a constant value for stress exceeding 135 MPa. This flattening of the FE peak intensity may be due to the transfer of electrons in the exciton system from the upper four valleys to the lower two valleys of the conduction band. As a matter of fact, around 135 MPa, the intensities of TO- and LO-phonon replicas of hFE start to decrease as shown in Fig. 8. The intervalley TA phonon is expected to play an important role in the relaxation of the "hot" excitons, since the energy of the TA phonon at the X point is nearly equal to the energy difference ~ 17 meV between the upper valley and the lower valley at 135 MPa.[29] No phonons are available for intervalley transition below 135 MPa. Above 135 MPa, the "hot" exciton can relax to the "cold" exciton by emitting an intervalley TA phonon. The FE luminescence intensity decreases almost to 70% at 150 MPa, compared with the zero-stress luminescence.

Figure 9 shows stress dependence of the photoluminescence intensity of FE(LA) in Ge by Ar^+-laser excitation. With stress two new peaks are split out on both sides of the main peak of FE(LA) at zero stress as shown in Fig. 4. After splitting, the luminescence intensity of the hFE(LA) peak is first slowly decreasing with stress. After 95 MPa, the peak intensity sharply decreases. The peak intensity of hhFE(LA) shows similar behavior. The peak intensity of lhFE(LA) decreases nearly exponentially with stress. The luminescence intensity at 150 MPa is nearly one-twelfth of that at zero stress. The reason for the decrease of FE(TO/LO) luminescence in Si and that of FE(LA) luminescence in Ge with stress is not so clear. We have been speculating, however, on some probable reasons, which we briefly reported in our earlier paper (Ref. 16). In this paper we shall try to explain it in more detail.

The PL intensity due to the radiative recombination of free excitons can be expressed as

$$I_{FE} = B n_{ex} , \quad (10)$$

where B is a constant and n_{ex} is the concentration of free excitons, whose temporal decay is given by the rate equation

$$dn_{ex}/dt = G_{ex} - n_{ex}/\tau_{ex} - \alpha_{ex} n_{ex} , \quad (11)$$

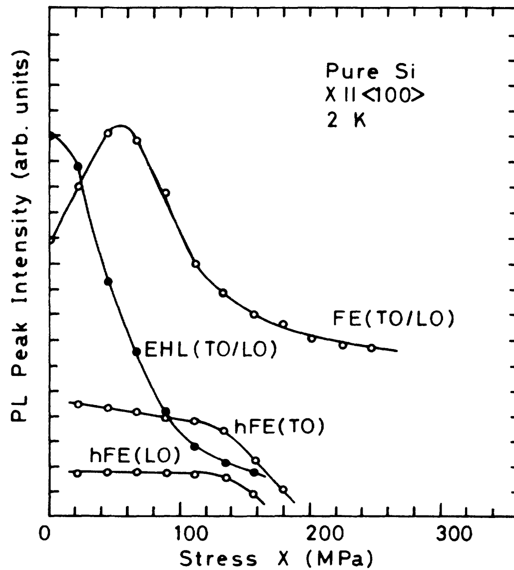

FIG. 8. The photoluminescence intensities of various peaks observed in Si are plotted at 2 K against stress. The EHL peak disappears at 157 MPa. The hFE lines with TO and LO phonons disappear below 200 MPa.

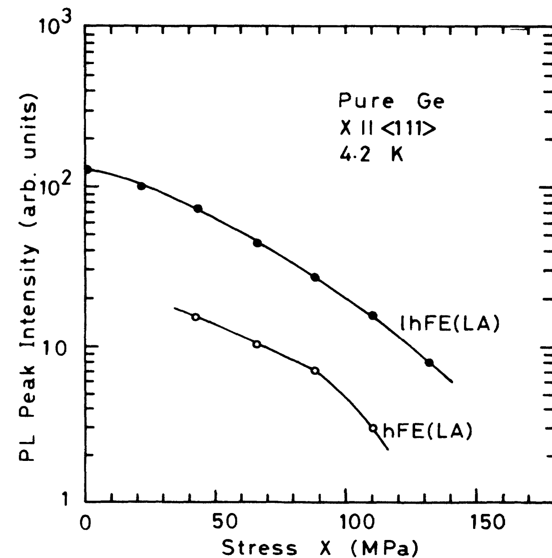

FIG. 9. The photoluminescence intensities of various peaks observed in pure Ge are plotted at 4.2 K as a function of stress.

where G_{ex} is the generation rate of excitons, $\alpha_{ex} = \gamma_{ex} N \exp(-E_x/k_B T)$ the thermal dissociation coefficient of excitons, E_x the ground-state binding energy of excitons, $N = (2\pi\mu k_B T/h^2)^{3/2}$ the effective density of states in which $1/\mu = 1/m_e + 1/m_h$ gives the reduced mass of the exciton, and τ_{ex} the recombination lifetime of free excitons. Under steady-state conditions, Eq. (11) should be equal to zero, so that we can easily estimate the concentration of excitons:

$$n_{ex} = G_{ex}/\tau_{ap} , \tag{12}$$

where $\tau_{ap} = (1/\tau_{ex} + \alpha_{ex})$ is the apparent decay time of the exciton.

The recombination lifetime of excitons τ_{ex} in semiconductors is another controversial point. We have measured the apparent lifetime of free excitons τ_{ap} under uniaxial stress. That accounts for both recombination and dissociation. At zero stress the apparent lifetime of FE in Si is ~ 0.97 μs, which is comparable with other authors' values.[30] With increasing stress the apparent lifetime of FE remains almost constant. The recombination lifetime of excitons in Si has been explained by Auger recombination after the formation of bound excitons. Under low stress, the signal due to bound excitons dissappears, so that this mechanism is not applicable to our case. However, there is a possibility that residual impurities can be recombination centers for excitons even in high stress. The apparent lifetime of the S peak in Si, on the other hand, remarkably decreases from 1.32 μs at 67 MPa to 0.58 μs at 180 MPa as shown in Fig. 10. The decrease in lifetime of the S peak is not linear with stress.

Balslev[22] showed that the change in the effective mass caused a decrease in excitonic binding energy of about 0.5 meV in Si. Shaklee and Nahory[31] measured the excitonic binding energy in Si at zero stress to be 14.7 meV. The effective-mass equation for indirect excitons in Ge was solved by Altarelli and Lipari.[32] They took the degeneracy and anisotropy of the bands into account. The calculated binding energies of the anisotropy split ground states (4.18 and 3.17 meV) are in excellent agreement with experiment (4.15 and 3.14 meV).[33]

The apparent lifetime of FE(LA) in Ge at zero stress is 5.6 μs, which agrees with other authors' values.[34] The lifetime of the 1hFE(LA) peak decreases with stress from 2.3 μs at 22 MPa to 0.8 μs at 67 MPa, as shown in Fig. 11. The decrease of 1hFE(LA) lifetime is not linear with stress. In Ge, the binding energy of the exciton is 4.2 meV without stress, which is small in comparison with the Si case, so that the thermal dissociation is important especially under stress. The thermal dissociation coefficient of free excitons is given by

$$\alpha_{ex} = \gamma_{ex}(2\pi\mu k_B T/h^2)^{3/2} \exp(-E_x/k_B T) . \tag{13}$$

One can take it as a constant at equilibrium. At such low temperature as $k_B T \ll E_x$, the thermal dissociation (by phonon absorption) rate becomes negligible. At 2 K in Si, $k_B T \ll E_x$ and at 4.2 K in Ge, $k_B T < E_x$. Therefore, the thermal dissociation rate in Ge at 4.2 K is much higher than that in Si at 2 K. The band gaps of Si and Ge decrease with stress and the band structures are simplified. We have seen that the excitonic binding energy first sharply decreases with increasing stress and then it seems to stand at a constant value at high stress limit both in Si and Ge.[35,36] According to previous work the binding energy is about 2.6 meV in the high stress limit in Ge.[37,38] The thermal dissociation rate will then drastically increase with stress. The concentration of free exci-

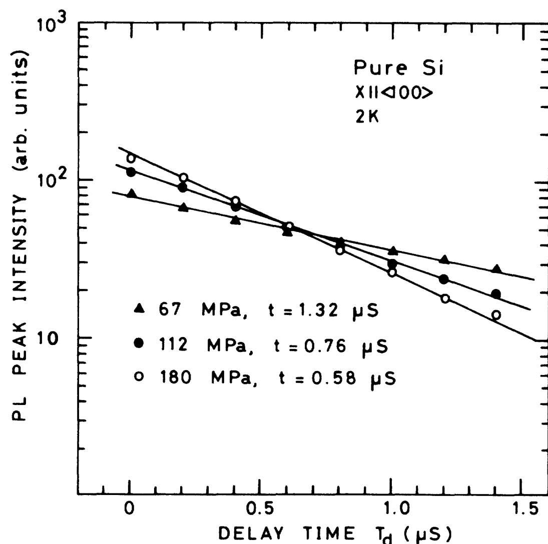

FIG. 10. The luminescence intensity of the S peak in pure Si is plotted at 2 K as a function of delay time T_d in time-resolved measurements under different uniaxial stresses. The lifetime t of the S peak decreases with stress.

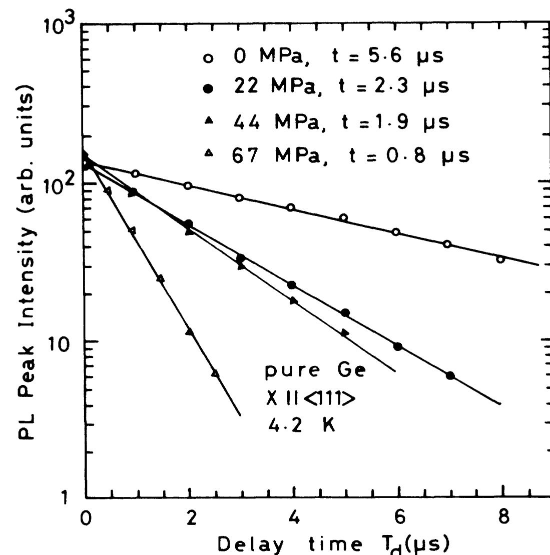

FIG. 11. The photoluminescence intensity of the 1hFE(LA) peak in Ge is plotted at 4.2 K as a function of delay time T_d from time-resolved measurements under different uniaxial stresses. The lifetime of the 1hFE(LA) peak decreases with stress.

tons $n_{\rm ex}$ should decrease from the zero-stress value. The decrease of apparent lifetime $\tau_{\rm ap}$ in Ge with stress may partly be due to the thermal dissociation of excitons. In order to analyze the data, we need detailed information on the stress dependence of the excitonic binding energy in Ge. In Si, the binding energy of the exciton is large enough compared with k_BT. Even if the binding energy decreases a bit under stress, the thermal energy is not able to catch up. The thermal dissociation coefficient will hardly be enhanced.

A. Holes under uniaxial stress

At zero stress light and heavy holes can coexist in the momentum space at $k=0$. Stress removes this degeneracy. The splitting of light- and heavy-hole valence bands depends linearly on the applied uniaxial stress. The relative population of light holes should decrease with stress on account of the increase of splitting energy. Light-hole-related hot-exciton luminescence has been proved under uniaxial stress by detecting the photon signal above the band-gap energy at

$$h\nu=E_g+\Delta E_{\rm VB}-\hbar\omega_p-E_x\ , \tag{14}$$

where E_g is the band-gap energy between the down valley of the conduction band and the heavy-hole valence band at $k=0$, $\Delta E_{\rm VB}$ is the energy difference between the stress-split heavy- and light-hole bands, $\hbar\omega_p$ is the assistant phonon energy, and E_x is the hot-exciton binding energy. Figure 12 shows the luminescence intensity of light-hole-related hot exciton (S peak) in pure Si against excitation intensity. The luminescence intensity of the S peak increases with stress. This indicates that the population of light-hole-related hot excitons is enhanced with uniaxial stress. The threshold excitation power to observe this luminescence line seems to increase with stress. This we can see by extrapolating our data at each stress to the lower excitation power, as shown in Fig. 12. In Ge, we also observe similar types of behavior of holes in the stress-split valence bands. The luminescence intensity of the light-hole-related hot excitons is stronger than other peaks, as already shown in Fig. 4. To explain why the light hole can be populated and enhanced in the stress-split valence band with uniaxial stress, we will examine some possibilities below.

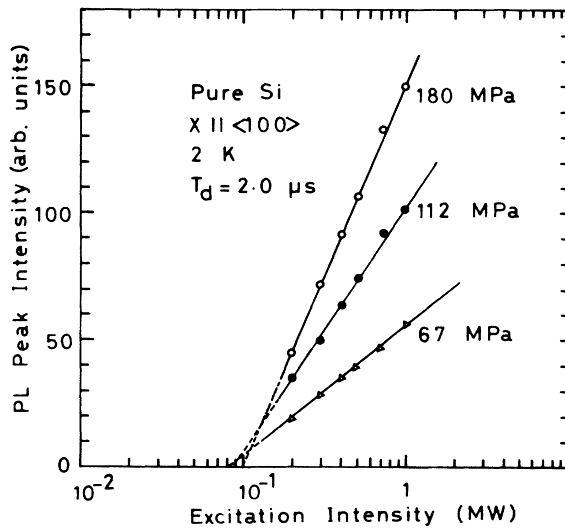

FIG. 12. The photoluminescence intensity of the S peak in pure Si is plotted at 2 K as a function of excitation power from dye laser in different stresses. The intensity of the S peak increases with stress. The threshold excitation power increases with stress as shown by extrapolation of the data points.

The S peak in Si appears in a high-excitation intensity region. The interaction between excitons is important to explain the S peak. There are two possibilities: one is simple exciton-exciton scattering, while the other is exciton-exciton Auger recombination. In the first process, one exciton collides with another and it is raised to light-hole-related exciton band. In the second process, two excitons collide with each other and one of them recombines nonradiatively to ionize the other exciton. The hole from the ionized exciton is elevated in energy to the light-hole band and again captures an electron to form a light-hole-related exciton. For the moment, we cannot conclude which process is more dominant.

The second process seems important to interpret the lifetime shortening of the S peak shown in Fig. 10. The apparent lifetime τ_s of the S peak decreases with increasing stress, while the luminescence intensity I_s of the S peak is enhanced by stress. From these observations, and after close examination of Fig. 10 and Fig. 12, we obtain a relation of the form

$$1/\tau_s=AI_s\ , \tag{15}$$

where A is some constant. This relation indicates that if a light-hole-related exciton meets another, one of them recombines. It thus seems that the exciton-exciton Auger recombination process is important in the high-density exciton case.

B. Auger recombination process

As an explanation of nonradiative recombination in semiconductors at high carrier densities and at transition energies that are greater than the energy of photons, Auger recombination is usually considered. The simplest Auger recombination is a three-particle process, involving one electron and two holes or two electrons and one hole. The recombination probability is thus proportional to n^2p or np^2, n and p being the concentrations of electrons and holes, respectively.[39]

The decay rate of photoexcited carriers in Si at low temperature is greatly controlled by the presence of shallow acceptors. For example, the free-exciton lifetime in undoped Si is 2.6 μs. If Si is doped with In at a level of 10^{15} cm^{-3}, the lifetime of photoexcited carriers (at low excitation) is reduced to less than 5 ns.[40] In contrast to Si, doping Ge with shallow acceptors at the 10^{15} cm^{-3} level has little effect on the lifetime of photoexcited carriers for temperature and excitation conditions at which EHL is not formed. In Si, the holes in the acceptor

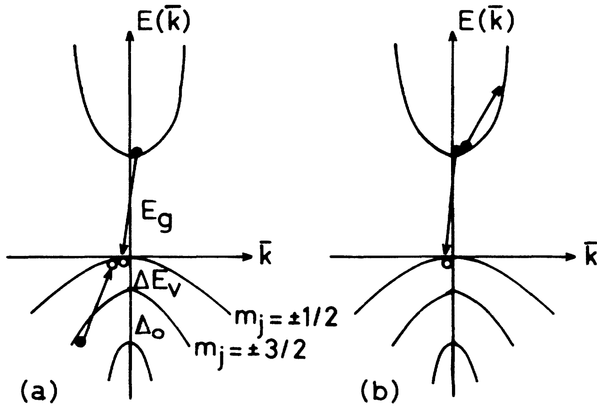

FIG. 13. Schematic diagram of the Auger recombination process in semiconductors: (a) *hhe* process and (b) *eeh* process.

bound excitons (BE) are well localized, resulting in large hole wave function spreading in momentum space and a fast Auger rate.

The dependence on acceptor type occurs because the acceptors with larger binding energy bind the holes more tightly, leading to faster Auger rates. In Ge, the holes in the acceptor BE are not tightly bound, so that the hole wave function spreading is small in momentum space and the Auger rate is slow.

An excitonic band-to-band Auger recombination mechanism is the process analogous to the excitonic Auger capture process which has been shown to explain the nonradiative recombination via deep impurity levels in Si.[41] Excitonic band-to-band recombination means a collision of a free exciton with a free carrier, where an electron and a hole recombine nonradiatively transferring their excess energy to the third particle, which is highly excited into its band, as shown in Fig. 13. Due to the spatial correlation of electron and hole within the exciton, this is effectively a bimolecular recombination process (Ref. 41).

As depicted in Fig. 13(a), the hole-hole-electron (*hhe*) Auger process generating holes in the stress-split-off valence band is possible with small momentum transfer which can recombine radiatively with the conduction-band electrons. Betzler[14] and Hangleiter[15] also observed the hot charge carriers produced by Auger process in highly excited (Watt order) Si at low temperature. In their explanation, the highly excited hole, which has taken over the electron-capture energy, recombines radiatively with a second electron in the conduction band while it relaxes back to the valence-band maximum. The *hhe* Auger process is the highly dominating process in the *p*-type Si and Ge under high excitation at low temperature. The probability of an Auger capture process is strongly enhanced by the excitonic localization of the electron-hole pairs (Ref. 15).

C. Generation rate of excitons

We can estimate the generation rate of excitons by using Eqs. (10) and (12). The observed apparent exciton lifetime τ_{ap} in Si keeps constant with increasing stress, so that PL intensity is proportional to the generation rate of excitons G_{ex}. Then the generation rate of cold excitons (FE) is expected to follow the behavior of PL intensity.

Barrau *et al.*[42] experimentally investigated in Si the cross section of the binding of an electron and a hole into an exciton. The value obtained by them for the binding coefficient is $\gamma_{ex}=0.9\times10^{-3}(T[\mathrm{K}])^{-2}$ cm^3 s^{-1} in the temperature interval 4–13 K, where T is in degrees kelvin. Avakumov *et al.*[43] also calculated the binding coefficient for Si by assuming the interaction of holes with phonons. They yielded a value of $5\times10^{-3}(T[\mathrm{K}])^{-2}$ cm^3 s^{-1}. Actually, the same result is obtained even if one assumes that the principal role is played by electrons.

If the effective temperature of electrons or holes depends on stress, the capture cross section of an electron and a hole may vary with stress. In contrast to the case of Si, τ_{ap} of 1hFE in Ge decreases considerably with increasing stress as shown in Fig. 11. The generation rate G_{ex} for 1hFE at 67 MPa is about twice as high as that at zero stress. The stress-enhanced generation of 1hFE in Ge is the same phenomenon as the emergence of the S peak in Si, since both peaks are light-hole-related hot excitons. At low temperatures, many excitons are created and they collide with each other in highly excited Ge or Si. After collision, some excitons may be excited to light-hole-related exciton states or upper-valley-electron-related states. The Bohr radius a_{ex} of an exciton in Ge is about 180 Å and that in Si is about 50 Å. The cross section of exciton-exciton scattering is proportional to a_{ex}^2. Then the cross section for Ge is 1 order as large as that for Si. Thus in the Ge case, even under the Ar$^+$-laser excitation, light-hole-related hot excitons can be observed.

V. CONCLUSIONS

We have investigated the effect of uniaxial stress on free excitons at low temperatures in Si and Ge under different intensities of excitation. The behavior of FE with stress is rather unexpected both in Si and in Ge. Under high excitation, an unknown PL peak is split out to the higher-energy side of FE in Si with stress. The splitting energy of this unknown peak from the FE peak is comparable with the splitting energy of the light- and heavy-hole valence bands with stress. We speculate this unknown peak is coming from the "hot exciton" related with light holes in the stress-split valence band. The population of hot excitons related with light holes in the stress-split valence band may be due to the exciton-exciton Auger excitation and/or exciton-exciton scattering. In Ge, we also observe a similar type of behavior of FE(LA) with stress at 200-mW excitation. The band structure of Ge is more sensitive to stress than that of Si. The FE(LA) peak of Ge is split into three peaks and the peak energy separations between the split peaks become larger with stress. Uniaxial stress enhances the population of Auger-excited holes while the lifetime of hot excitons decreases with stress both in Si and in Ge.

The luminescence intensity of FE in Si and Ge decreases exponentially with increasing stress. The reason

for this decrease is due to the decrease of excitonic binding energy with increasing stress. The FE luminescence intensity decreases in pure Si down to 70% and in Ge to one-twelfth at 150 MPa in comparison with the zero-stress luminescence. We speculate this decrease to be due to the decrease of the generation rate of excitons with stress. In Ge, the thermal dissociation (by phonon absorption) of excitons may be responsible for the drastic decrease of FE(LA) luminescence intensity with stress, as we discussed in Sec. IV. The intervalley TA phonon is expected to be important in the relaxation of the hot exciton around 135-MPa stress in Si.

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