Shear-deformation-potential constant of the conduction-band minima of Si: Experimental determination by the deep-level capacitance transient method

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The shear-deformation-potential constant Ξ_u of the conduction-band minima of Si has been measured by a method which we called deep-level capacitance transient under uniaxial stress. The uniaxial-stress (F) dependence of the electron emission rate e_n from deep levels to the split conduction-band minima of Si has been analyzed. Theoretical curves are in good agreement with experimental data for the S^0 and S^+ deep levels in Si. The values of Ξ_u obtained by the method are 11.1±0.3 eV at 148.9 K and 11.3±0.3 eV at 223.6 K. The analysis and the Ξ_u values obtained are also valuable for symmetry determination of deep electron traps in Si.

I. INTRODUCTION

The shear-deformation-potential constant Ξ_u of the conduction band was introduced as early as in 1958 by Herring and Vogt,[1] and it has been determined experimentally by a variety of different techniques[2–14] because of its importance in semiconductor physics. Unfortunately, the values of Ξ_u determined by different techniques are quite different, ranging from 7 to 11 eV. On the other hand, most of these methods are quite involved or indirect with possible uncertainties as will be discussed in Sec. V.

The purpose of this work is to provide a method to determine the parameter Ξ_u. A short report[15] has been presented and we will describe it in detail in this paper. The method is based on the constant-temperature deep-level capacitance transient technique.[16] A deep level is used only as a reference level in the gap and the value of the deformation potential constant Ξ_u is obtained straightforwardly from the change of emission rate e_n of the electrons from the deep traps to the conduction-band minima due to applied uniaxial stress. Since the method is simple and direct with no ambiguous parameters, the results should be reliable.

The Ξ_u value obtained by this method is particularly valuable for uniaxial-stress deep-level transient measurements for symmetry determination of deep centers in semiconductors, where the splitting of the minima of the conduction bands plays a main obstacle for precise determination of deep-level shift and splitting under uniaxial stress.[17]

We will divide the paper as follows: In Sec. II, the principle of the deep-level capacitance transient method for determining Ξ_u will be discussed. In Sec. III, experimental details and measurements will be outlined. In Sec. IV, experimental results will be given. In Sec. V we will compare our method to various existing methods. In Sec. VI we will present some concluding remarks.

II. PRINCIPLE OF THE METHOD— RECOMBINATION KINETICS OF DEEP LEVELS UNDER UNIAXIAL STRESS

In this section we discuss the principle of deep-level transient measurements as a means to determine Ξ_u. We first generalize the Shockley-Read-Hall recombination kinetic theory of deep traps[18] to the case when the minima of the conduction bands $E_c^{(i)}$ ($i=1-6$ for Si) are lifted from degeneracy under uniaxial stress. This problem was first discussed by Yao *et al.*[19] Here we follow the approach by Li,[17] which is most appropriate for our purpose.

The original argument of Li includes the general case where the conduction-band minima E_c and deep level E_T are both degenerate. In this work, a deep level E_T is introduced by sulfur impurities. Ludwig[20] has identified the symmetry of the deep-level wave function of an isolated S^+ center to be A_1, by electron spin resonance techniques. Therefore, E_T is nondegenerate and the analysis can be simplified.

The rate of emission per unit volume of the electrons from the deep levels E_T to the jth conduction-band minimum is $e_n^{(j)}n_T$. Here $e_n^{(j)}$ is the emission rate and n_T is the electron concentration of E_T levels. The rate of capture of the electrons from the jth conduction-band minimum to the deep levels E_T is $C_n^{(j)}n^{(j)}P_T$. Here $C_n^{(j)}$ is the capture rate in $\mathrm{cm}^3\mathrm{s}^{-1}$, $n^{(j)}$ is the electron concentration in the jth conduction-band minimum, $P_T=(N_{TT}-n_T)$ is the hole concentration of E_T levels, and N_{TT} is the S impurity concentration. At thermal equilibrium, we have

$$\sum_{j=1}^{l} C_n^{(j)}n^{(j)}P_T=\sum_{j=1}^{l} e_n^{(j)}n_T \ . \tag{1}$$

We introduce

$$\sum_{j=1}^{l} e_n^{(j)}=e_n \ , \tag{2a}$$

$$\overline{C_n}=\sum_{j=1}^{l} C_n^{(j)}n^{(j)}\Big/\sum_{j=1}^{l} n^{(j)} \ , \tag{2b}$$

and

$$E_c^{(j)}=\overline{E_c}+\delta E_c^{(j)} \ , \tag{3a}$$

$$\overline{E_c}=\sum_{j=1}^{l} E_c^{(j)}/l \ , \tag{3b}$$

$$g_c^{-1}=\sum_{j=1}^{l} e^{-\delta E_e^{(j)}/k_B} \ . \tag{3c}$$

Here $l=6$ for the case of Si. On the other hand, we have

$$n_T=N_{TT}f_T \ ,$$

$$f_T=\frac{1}{1+e^{(E_T-E_F)/k_B}} \ , \tag{4}$$

$$n^{(j)}=N_c e^{-(E_c^{(j)}-E_F)/k_B} \ , \tag{5}$$

and

$$N_c=\frac{2(2\pi m_c^* k_B)^{3/2}}{h^3} \ . \tag{6}$$

Here E_F is the Fermi energy and m_c^* is the effective mass at conduction-band minima. From previous piezoresistance experiments, the stress dependence of the effective mass of the conduction band for Si is very weak.[21] From the data of Ref. 21, the estimated change of $(1/m_c^*)(dm_c^*/dF)$ is less than 10^{-3}/kbar. Therefore, it is justified to neglect the stress dependence of m_c^* in our experiment.

Substituting Eqs. (2)–(6) into Eq. (1) we obtain

$$e_n=g_c^{-1}\overline{C_n}N_c e^{-(\overline{E_c}-E_T)/k_B} \ . \tag{7}$$

The rate equation of n_T is modified to

$$\frac{dn_T}{dt}=-(e_n+\overline{C_n}n)n_T+\overline{C_n}nN_{TT} \ , \tag{8}$$

where $n=\sum_{j=1}^{l}n^{(j)}$ is the carrier concentration.

Equation (8) is exactly the same rate equation for the case without stress.[16] Therefore, e_n and $\overline{C_n}$ can be measured by well-known constant-temperature capacitance transient experiments with emission-time constant e_n^{-1} (Ref. 16) and capture-time constant $(e_n+\overline{C_n}n)^{-1}\approx(\overline{C_n}n)^{-1}$.[22]

Following Herring's deformation-potential analysis,[1] the shift in energy of the jth minimum for Si is given by

$$\Delta E_c^{(j)}=\sum_{\alpha,\beta}(\Xi_d\delta_{\alpha\beta}+\Xi_u K_\alpha^{(j)}K_\beta^{(j)})u_{\alpha\beta} \ , \tag{9}$$

where $K_\alpha^{(j)}$ and $K_\beta^{(j)}$ are components of a unit vector pointing from the center of the Brillouin zone towards the position in k space of the jth conduction-band minimum. The subindex α or β designates a component along one of the cubic axes of the crystal, and $u_{\alpha\beta}$ are components of the strain tensor. The symbols Ξ_d and Ξ_u are the volume and shear deformation potential constants, respectively.

$\Delta E_c^{(j)}$ in Eq. (9) can be divided into two parts:

$$\Delta E_c^{(j)}=\Delta\overline{E_c}+\delta E_c^{(j)} \ , \tag{10}$$

where $\overline{E_c}$ and $\delta E_c^{(j)}$ are defined by Eqs. (3b) and (3a). By Eqs. (9) and (10) the shift of the average energy $\overline{E_c}$ is given by

$$\Delta\overline{E_c}=(\Xi_d+\tfrac{1}{3}\Xi_u)\mathrm{Tr}\vec{\vec{u}} \ . \tag{11}$$

The shift of the jth minimum with respect to $\overline{E_c}$ is given by

$$\delta E_c^{(j)}=\Xi_u\left[\left[\sum_{\alpha,\beta}K_\alpha^{(j)}K_\beta^{(j)}u_{\alpha\beta}\right]-\tfrac{1}{3}\mathrm{Tr}\vec{\vec{u}}\right] \ . \tag{12}$$

The strain components $u_{\alpha\beta}$ are related to stress components $\sigma_{\alpha\beta}$ by the elastic constants $S_{\alpha\beta}$ for cubic crystals as follows:[23]

$$\begin{bmatrix} u_{xx}\\ u_{yy}\\ u_{zz}\\ u_{yz}\\ u_{zx}\\ u_{xy}\end{bmatrix}=\begin{bmatrix} S_{11} & S_{12} & S_{12} & 0 & 0 & 0\\ S_{12} & S_{11} & S_{12} & 0 & 0 & 0\\ S_{12} & S_{12} & S_{11} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{2}S_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{2}S_{44} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2}S_{44}\end{bmatrix}\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{zx}\\ \sigma_{xy}\end{bmatrix} \ . \tag{13}$$

For uniaxial compression along the [100] direction, the stress tensor $\sigma_{\alpha\beta}$ is expressed by

$$(\sigma_{\alpha\beta})=-F\begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix} \ , \tag{14}$$

where F is the compression force per unit cross-sectional area. Combining Eqs. (12)–(14), we obtain

$$\delta E_c^{(j)}=\begin{cases}-\frac{2}{3}F\Xi_u(S_{11}-S_{12}) \ , & j=1,2\\ \frac{1}{3}F\Xi_u(S_{11}-S_{12}) \ , & j=3,4,5,6 \ ,\end{cases} \tag{15}$$

where $j=1,2$ correspond to two minima with $\mathbf{K}^{(j)}$ parallel to the stress direction while the rest correspond to the other four perpendicular directions.

From Eqs. (3c), (7), and (15), we have

$$\ln e_n = \ln g_c^{-1} + \ln \overline{C_n} + \ln N_c - \frac{1}{k_B T}(\overline{E_c} - E_T) . \quad (16)$$

Defining

$$x = \tfrac{1}{3} F \Xi_u (S_{11} - S_{12})/k_B T , \quad (17)$$

we get

$$g_c^{-1} = 4e^{-x} + 2e^{2x} . \quad (18)$$

We notice that $3x$ is just the splitting of the conduction-band minima in unit of $k_B T$. In Eq. (16) the capture rate $\overline{C_n}$ of the electrons is independent of the stress within experimental uncertainty for the case of the S deep level, as will be discussed in Sec. IV.

From these considerations the shift of $\ln e_n$ under stress is obtained by

$$\Delta(\ln e_n) = \Delta(\ln g_c^{-1}) - \frac{1}{k_B T}\Delta(\overline{E_c} - E_T) . \quad (16')$$

For the low-stress limit $x \ll 1$, Eq. (16) reduces to

$$\Delta e_n \doteq \left.\frac{\partial \ln e_n}{\partial F}\right|_{F\to 0} F + \frac{\Xi_u^2 (S_{11}-S_{12})^2}{3(k_B T)^2} F^2 , \quad (19)$$

with[17]

$$\left.\frac{\partial \ln e_n}{\partial F}\right|_{F\to 0} = \frac{1}{k_B T}\frac{\partial (E_T - \overline{E_c})}{\partial F} . \quad (19')$$

The physical meaning of Eq. (19') is apparent. When the splitting between conduction-band minima is small in comparison to $k_B T$, the Boltzmann factor e^x in Eq. (4) is linearly dependent on x. Therefore, the deep level sees the conduction-band minima in average distance. The variation of $\ln e_n$ under stress is mainly determined by the variation of $\overline{E_c} - E_T$; the splitting of the conduction band can be treated as a small perturbation proportional to F^2.

In large-stress limit, i.e., $3x \gg 1$, Eq. (16') reduces to

$$\left.\frac{\partial \ln e_n}{\partial F}\right|_{F\to\infty} = -\frac{1}{k_B T}\left[\frac{\partial (E_c^{(1)} - E_T)}{\partial F}\right] . \quad (20)$$

In other words, when the splitting of the conduction-band minima is large in comparison to $k_B T$, the deep level only sees the lower conduction-band minima $E_c^{(1)}$ and $E_c^{(2)}$, since almost no electrons occupy the higher minima. From Eqs. (15), (19'), and (20) one obtains

$$\Xi_u = \frac{3k_B T}{2(S_{11}-S_{12})}\left[\left.\frac{\partial \ln e_n}{\partial F}\right|_{F\to\infty} - \left.\frac{\partial \ln e_n}{\partial F}\right|_{F=0}\right] . \quad (21)$$

The first term in the large parentheses $F_1 = (\partial/\partial F)\ln e_n|_{F\to\infty}$ can be determined from experimental data of $\ln e_n$ versus F by taking the high limit. The second term $F_2 = (\partial/\partial F)\ln e_n|_{F=0}$ is obtained by the following iteration procedure: As F_1 is an order of magnitude larger than F_2, Eqs. (19) and (21) are a pair of weakly coupled equations with two parameters F_2 and Ξ_u. For the first iteration, we neglect F_2 in Eq. (21) to obtain the value for Ξ_u. Using the Ξ_u thus obtained and Eq. (19) to fit the experimental curve of $\ln e_n$ versus F, the value of F_2 is obtained. For the second iteration, we put the value of F_2 from the first iteration into Eq. (21), and a new Ξ_u is obtained. The process continues until converged F_2 and Ξ_u are achieved.

III. EXPERIMENTAL DETAILS AND MEASUREMENTS

A. Sample preparation

$N_d = 3\times 10^{15}$ cm^{-3} phosphorous-doped Si single crystals prepared by the Czochralski method were x-ray-oriented in the [100] direction within 0.1° and cut in samples with 1×0.7-mm^2 cross section and 7 mm in length. P^+-n junctions with $\Phi = 0.6$ mm located at the middle of the 7×1-mm^2 side surface were made by boron diffusion. The samples were checked by deep-level transient spectroscopy (DLTS) measurements with no detectable deep impurities. The samples were subsequently placed in a quartz ampoule with 2 mg of 99.999% sulfur and evacuated to 1×10^{-5} Torr and sealed. The diffusion temperature was 1180 °C for 2 h. Typical DLTS spectra with S^0 and S^+ peaks were obtained for the samples with capacitance transient amplitude rate $\Delta C/C \sim 0.01$ at 10-V bias. By $\delta C/C \sim \frac{1}{2}(N_{TT}/N_d)$, the S concentration was estimated to be 6×10^{13} cm^{-3}.

B. Stress apparatus

Figure 1 shows the schematic diagram of the stress apparatus. It consists of a sample holder (A), a semi-ball-shaped top block (B) with the surface adjustable to fit the top surface of the sample (C), and a bottom rod (D). The bottom rod is constrained to move along the stress direction and is lifted by means of a lever (E) through the rod (F) and frame (G). Weights are hung on the lever arm. The lever is mounted on a platform (H) which also supports the sample holder (A) by a pipe (P). The force applied to the sample can be precisely calibrated by this stress apparatus. The cross-sectional area of the sample was measured with a depth gauge; this was checked by a scaled optical microscope. The accuracy of the measurement of the cross-sectional area was estimated to be about 1%.

C. Measurement

The emission rate e_n was determined by measuring the capacitance transient signal at constant temperature. The measurements were carried out by a computer-controlled data-acquisition system, as shown in Fig. 2. The junction capacitance was measured by a Boonton 72 B capacitance meter at 1-MHz frequency. For every cycle of capacitance transient, 15 capacitance data were read sequentially by a HP3456A digital voltmeter and then were fed into the computer. The temperature stabil-

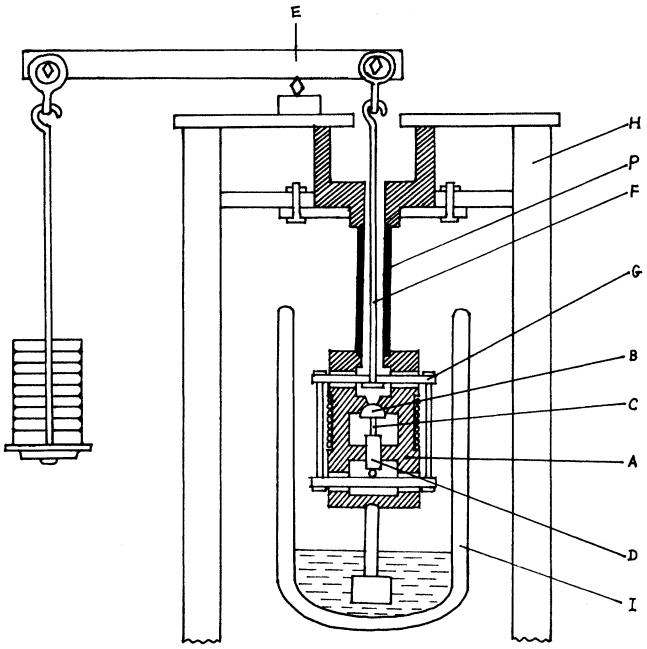

FIG. 1. Uniaxial stress apparatus: (*A*) Sample holder; (*B*) semi-ball-shaped top block; (*C*) sample; (*D*) bottom rod; (*E*) lever; (*F*) stainless steel rod; (*G*) frame; (*H*) support platform; (*I*) liquid-nitrogen Dewar; (*P*) pipe.

ity is extremely important, since the emission rate e_n is very sensitive to the temperature. According to Eq. (7),

$$\frac{de_n}{e_n} \doteq \frac{\overline{E_c}-E_T}{k_B T}\frac{dT}{T} , \tag{22}$$

if we neglect the weak temperature dependences of g_c^{-1}, $\overline{C_n}$, and N_c. In our system, temperature fluctuation was less than ± 0.03 K. For S^+ and S^0 levels, as listed in Table I, the corresponding relative changes de_n/e_n were ~ 3.7 and 4.7×10^{-3}, respectively. $2-5\times 10^2$ repeated measurements were taken and averaged to further reduce the fluctuations of e_n due to electrical and temperature fluctuations.

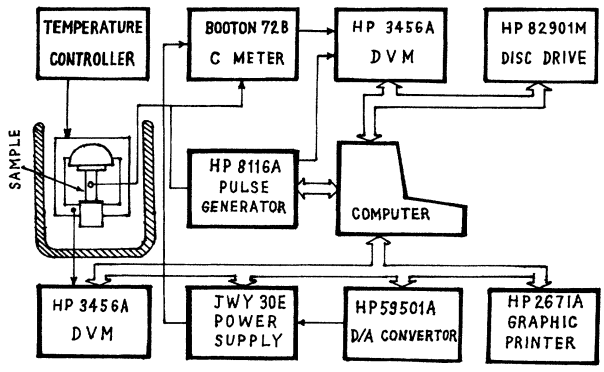

FIG. 2. Data-acquisition system for constant capacitance transient measurement under stress.

IV. EXPERIMENTAL RESULTS

DLTS spectra for typical S^+ and S^0 levels in Si were obtained.[24] From an Arrhenius plot, we obtain $\overline{E_c}-E_T=0.53$ eV for the S^+ and 0.30 eV for the S^0 levels, which are consistent with previous measurements.[16,24] For constant-temperature capacitance transient measurements, a transient signal with a single exponential time constant e_n^{-1} was recorded within the whole stress range of our measurement. The stress dependence of $\ln e_n$ is shown in Fig. 3 for the S^+ level and Fig. 4 for the S^0 level at 223.6 and 148.9 K, respectively. Figure 5 is a typical measurement that describes the relation between the initial capacitance transient amplitude $\Delta C(\tau)$ and the stress F for the S^0 level. The capture rate $\overline{C_n}$ can be evaluated from variation of $\Delta C(\tau)$ with τ. Here τ is the filling pulse length.[22] From Fig. 5, $\overline{C_n}$ is confirmed to be almost stress independent within the experimental accuracy. The previous hydrostatic experiments[25,26] have reported similar results that the electron capture rates of deep levels including S^0 and S^+ in Si are insensitive to hydrostatic pressure.

In practice, the curve-fitting procedure of Figs. 3 and 4 was as follows: Because the highest stress we could apply to the sample before sample breaking was not large enough to satisfy the condition $3x \gg 1$ of Sec. II, we were not able to obtain the precise value of $(\partial/\partial F)\ln e_n|_{F\to\infty}$ in Eq. (20) from the experiment. An alternative procedure was used. We used Eqs. (16)–(18) and Ξ_u as an adjustable parameter to fit the curve. As indicated in Figs. 3

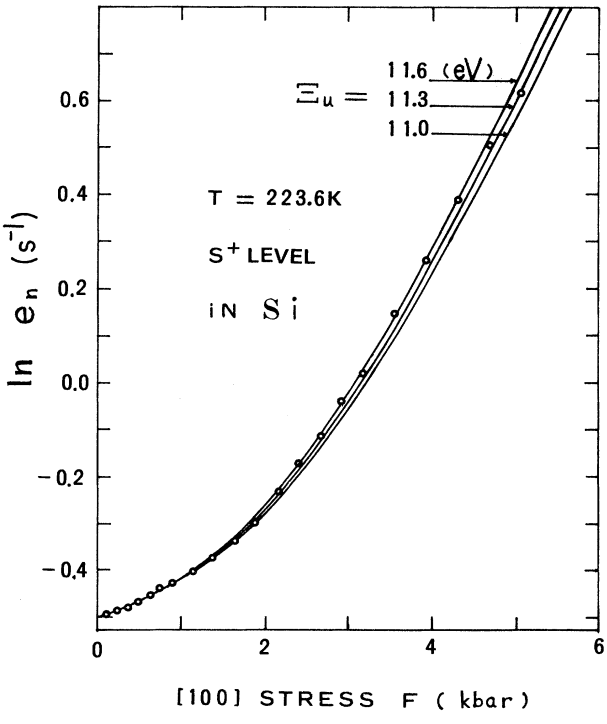

FIG. 3. Variation of emission rate of electrons $\overline{C_n}$ from S^+ levels to the conduction band of Si under [100] stress at 223.9 K.

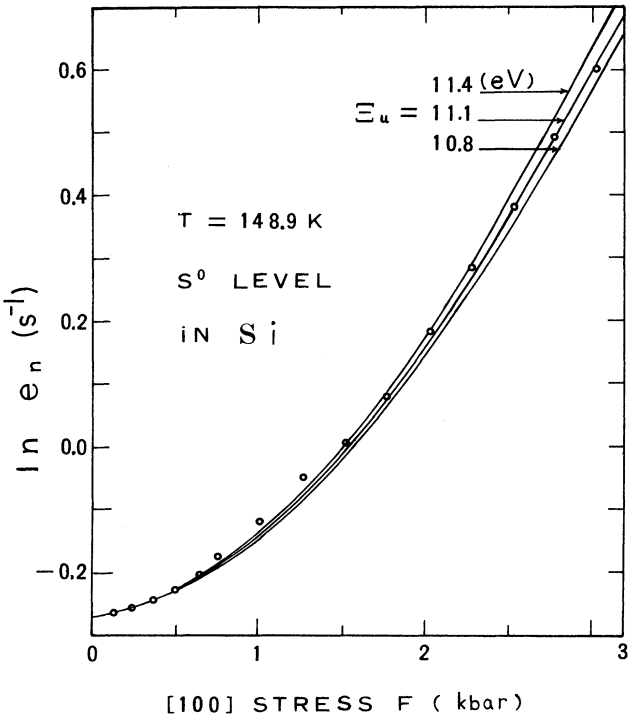

FIG. 4. Variation of emission rate of electrons $\overline{C_n}$ from S^0 levels to the conduction band of Si under [100] stres at 148.9 K.

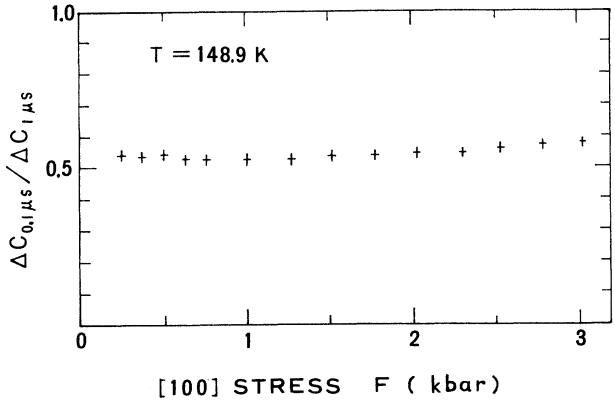

FIG. 5. $\Delta C_{0.1\,\mu s}/\Delta C_{1\,\mu s}$ vs [100] stress plot. $\Delta C_{1\,\mu s}$ is the initial capacitance transient amplitude with filling pulse length 1 μs. 1 μs is an order of magnitude larger than the capture-time constant τ_c. Therefore $\Delta C_{1\,\mu s}$ is saturated with this pulse length. $\Delta C_{0.1\,\mu s}$ is the initial capacitance transient amplitude with filling pulse length 0.1 μs. 0.1 μs is the same order of magnitude as τ_c. Any change of τ_c gives rise to change of $\Delta C_{0.1\,\mu s}/\Delta C_{1\,\mu s}$.

and 4, the curve fitting is sensitive to the value of Ξ_u.

The values of Ξ_u and $d(\overline{E_c}-E_T)/dF$ obtained by the iteration procedure are listed in Table I. By our previous analysis[26] for the defect Hamiltonian with T_d symmetry in cubic crystal, the uniaxial stress derivative $d(\overline{E_c}-E_T)/dF$ should be isotropic and equal to $\frac{1}{3}$ of the hydrostatic pressure derivative $d(\overline{E_c}-E_T)/dP$. Jantsch *et al.*[25] have reported $d(\overline{E_c}-E_T)/dP$ of S^0 and S^+ levels in Si to be -1.7 ± 0.1 and -2.05 ± 0.1 meV/kbar, respectively. In comparison with our results in Table I, the 1:3 rule is satisfied.

V. DISCUSSION

A. Assessment of existing experiments

A large variety of different methods has been used to determine the value of Ξ_u. Table II is a list of these methods. The values for Ξ_u determined by different methods lie in the range of 7–11 eV. Many of these methods were quite involved and less reliable. For instance, the method of number 12 in Table II measured the linewidth of cyclotron resonance to determine the carrier scattering relaxation time τ, and then used the theoretical formula of Herring and Vogt (HV) to obtain Ξ_u from τ. The equations of HV are rather complicated. The method numbered 14 was based on the effect of carrier concentration on elastic constants. Three equations were used to fit three parameters Ξ_u, Fermi energy E_F, and carrier concentration n. However, the values of E_F and n fitted from the experimental curves were not consistent with each other when Fermi statistics was used for calculating n. The piezoresistance method of number 13 was based on a hypothesis which has never been confirmed by experiments; there scattering mechanisms and mobilities were taken to be independent of stress. The piezo-optic method of number 2 suffers from uncertainties in determination of the carrier density by Hall-effect measurements due to lack of an exact knowledge of μ_H/μ. However, values of Ξ_u determined by the piezo-optic method are very close to those obtained in the present work.

On the other hand, some methods were indirect methods. The electric paramagnetic resonance methods numbered 3 and 4 were indirect, since the measured

TABLE I. Shear-deformation-potential constant Ξ_u and [100] stress derivative of S deep levels in Si.

Deep level	$\overline{E_c}-E_T$ (eV)	$d(\overline{E_c}-E_T)/dF$ (meV/kbar)	Ξ_u[a] (eV)	Temperature (K)
S^0	0.30	−0.57	11.1±0.3	148.9
S^+	0.53	−0.68	11.3±0.3	223.6

[a]The values of $(C_{11}-C_{12})=(S_{11}-S_{12})^{-1}=1.024\times10^{12}$ and 1.018×10^{12} dyn/cm^2 at 148.9 and 223.6 K are used, respectively, to deduce Ξ_u, as illustrated in the text. The values of C_{11} and C_{12} are taken from Ref. 27.

TABLE II. Comparison of Ξ_u's for Si determined by various methods.

Method	Ξ_u (eV)	Ref. no.
1. Deep-level transient method	11.1±0.3 (149 K) 11.3±0.3 (224 K)	this work
2. Piezo-optic effect	11.3±0.3 (300 K)	2
3. Electron paramagnetic resonance	11±1 (1.25 K)	3
4. Same as no. 3	11.4±1.1 (1.3–4 K)	4
5. Piezospectroscopy of indirect exciton absorption	8.6±0.2 (80 K) 9.2±0.3 (295 K)	5
6. Same as no. 5	8.3±0.4 (77 K)	6
7. Piezospectroscopy of indirect exciton spectrum	8.6±0.4 (77 K)	7
8. Same as no. 7	8.1±0.3	8
9. Piezospectroscopy of shallow-donor excited states (Sb,P,As,Mg)	8.77±0.07 (10 K)	13
10. Same as no. 9; (S)	7.9±0.2 (low K)	10
11. Same as no. 9; (P)	7.9±0.2 (10 K)	11
12. Linewidth of cyclotron resonance	8.5±0.1 (2.5–5 K)	12
13. Piezoresistance	8.3±0.3 (300 K)	13
14. Effect of carrier concentration on elastic constants	8.6±0.4 (298 K)	14

quantity is Ξ_u/E_{12}, where E_{12} is the splitting between the singlet and doublet of donor levels in Si. The piezospectroscopy methods of numbers 5–11 were also indirect methods, which relied upon the validity of effective-mass theory. Methods 5–8 measured the splitting of the indirect exciton lines under stress. This included not only the splittings due to conduction-band minima, but also possible splittings of binding energies of excitons attached to different valleys, and splittings of energies of phonons involved in indirect exciton absorption. Methods numbered 9–11 measured the splittings of the excited donor states under stress. This implicitly assumed that the ionization energies of excited donor states to the conduction-band minima were stress independent or had the same stress dependence.

Since the values of Ξ_u determined by different methods are quite diverse and most of these methods have different kinds of uncertainties and ambiguities, independent techniques based on different principles are still desirable and significant in resolving the discrepancies that still exist in the measurements of deformation potentials in semiconductors. The technique of the present work is an electrical measurement in nature and incorporates simple theory and equations. The method measures the splitting of conduction-band minima directly. Thus it should prove valuable for clarifying the controversy of the different values of Ξ_u obtained by different authors.

B. Possible temperature dependence of Ξ_u

It is indicated in Table I that the shear deformation potential of Si conduction-band minima Ξ_u is temperature dependent. In the linear temperature approximation, $d\Xi_u/dT \sim +3$ meV/K. The interesting fact to note is that from data of piezospectroscopy of Balslev,[5] a temperature coefficient of $d\Xi_u/dT \sim +3$ meV/K is also obtained. As has been pointed out by Brooks,[28] the energy term $E_c^{(j)}$ of Eq. (4) is actually the free energy, which is temperature dependent. From this context, Ξ_u, which measures the splitting of $E_c^{(j)}$ between different j, is reasonably temperature dependent. Furthermore, Van Vechten[29] has verified that the energy difference between two electronic states measured by no-phonon optical measurements should be equal to the free-energy difference between the same two states measured by thermal experiments.[24] Therefore, the temperature dependence of measured Ξ_u by methods 9–11 of Table II should be similar to the present work.

The arguments can also be used for methods 5–8 if the temperature dependences of the phonons participating in the absorption of indirect excitons attached to different minima are the same. Although the data of the present work and those given in Ref. 5 both indicate a temperature dependence of $\sim +3$ meV/K for Ξ_u, we feel that the result is not fully developed, and further experiments with higher accuracy and more temperature points are needed to confirm it.

VI. CONCLUDING DISCUSSIONS

We have developed a method—deep-level capacitance transient under uniaxial stress—to measure the shear deformation potential constant Ξ_u of the conduction band of Si. The technique is advantageous in its simplicity of the basic principle and formulation with parameters that can be measured precisely. The central theme of this method is the direct measurement of the splitting of the

conduction-band minima, which yields the values of $\Xi_u = 11.1 \pm 0.3$ eV at 148.9 K and 11.3 ± 0.3 eV at 223.6 K. The result is particularly valuable for symmetry determination of deep electron traps in Si by stress experiments.

ACKNOWLEDGMENTS

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