

# Auger coefficients for highly doped and highly excited silicon

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The recombination kinetics in highly doped *p*- and *n*-type silicon has been investigated at 77, 300, and 400 K through the radiative band-to-band recombination. The minority-carrier lifetime depends quadratically on the doping concentration as expected for Auger recombination. The Auger coefficients at 300 K for *p*- and *n*-type silicon are found to be  $C_p = 9.9 \times 10^{-32} \text{ cm}^6 \text{ s}^{-1}$  and  $C_n = 2.8 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$ . They are nearly independent of temperature in the range investigated. The Auger coefficient in highly excited pure silicon at 4.2 K (electron-hole drops) is essentially the same as in highly doped silicon.

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The predominant recombination mechanism in elemental semiconductors at high carrier or doping concentrations is an Auger process, as has been proved experimentally<sup>1-7</sup> and treated theoretically<sup>8-10</sup> in several papers. From simple reaction kinetics, it is expected that the recombination probability for this three-particle process depends on the carrier concentrations *n* and *p* according to  $p^2n$  for the *e-h-h* process and  $n^2p$  for the *e-e-h* process, respectively.

In Si, Auger processes have previously been studied in highly doped material as well as by high excitation of pure material. Beck and Conradt<sup>5</sup> investigated the band-to-band Auger process in highly doped Si bulk material with relatively weak excitation intensity, which allows the determination of both coefficients for the electron-hole-hole and electron-electron-hole process, respectively. The dependence of their experimentally observed carrier lifetime on the carrier density is definitely weaker than quadratic. However, lifetimes below  $10^{-7}$  s could not be determined exactly because of measuring technique reasons.

In this paper, we report measurements of the dependence of the minority-carrier lifetime on the majority-carrier concentration for *n*- and *p*-type silicon which were performed with an improved experimental setup allowing lifetime measurements down to 400 ps. Furthermore, the Auger coefficients were determined between 77 and 400 K and compared with those for highly excited silicon at liquid-helium temperature.

The minority-carrier lifetime was deduced from the decay time of the band-to-band recombination radiation after pulsed excitation by a mode-locked cavity-dumped Ar<sup>+</sup>-ion laser with a pulse width of 400 ps and a repetition rate of 10 kHz–1 MHz, corresponding to the time range selected for the detecting system. Most of the wafers investigated were Wacker Chemitronic float-zone dislocation-free crystals doped with P or B. Only a few samples of the highest doping level were grown by the Czochralski method. Several of the *n*-type samples were Sb and As doped.

The luminescence efficiency could be increased when

the surface recombination of the samples was reduced by careful etching. The radiation emitted from the sample was separated from the excitation light using a double-prism monochromator with wide slits, thus passing a broad spectrum of the recombination radiation at 1.1 eV.

As the quantum efficiency is extremely low, the luminescence was detected by a liquid-nitrogen-cooled S1-photomultiplier and recorded using the single-photon counting technique.<sup>11</sup> The time difference between a start signal, generated by the laser pulse and a stop signal, generated by the photomultiplier after detection of the first photon, is converted by a time-to-pulse-height converter to a time-proportional voltage pulse. This voltage is digitalized and stored in a multichannel analyzer, and after collection of a sufficient number of events, the stored pulse-height distribution will show the spectrum of emitted light intensity versus time, provided that the count rate was sufficiently low.

Since the excitation wavelength is 514.5 nm, the carriers are excited in a thin surface layer (about 1  $\mu\text{m}$ ). The general luminescence decay is exponential (Fig. 1), and the bulk minority-carrier lifetime can be

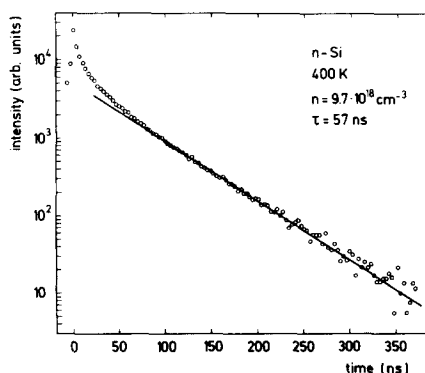


FIG. 1. Decay of luminescence emitted from highly doped *n*-type silicon bulk material at  $\lambda = 1.1 \mu\text{m}$  after excitation by a laser pulse at  $\lambda = 0.5145 \mu\text{m}$ .

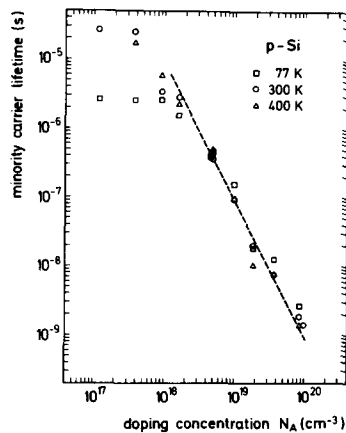


FIG. 2. Minority-carrier lifetime versus doping concentration in *p*-type silicon bulk material at 77, 300, and 400 K. The dashed line is the fit for 300 K and represents the quadratic dependence.

calculated by a least-squares fit. The initial stage of the decay may be faster, probably due to surface recombination and high-excitation effects.

In order to determine the carrier density, we measured the resistivity  $\rho$  and the Hall coefficient  $R_H$  using the van der Pauw geometry.<sup>12</sup> In the low magnetic induction limit ( $\mu B \ll 1$ ), which was fulfilled in all measurements, the carrier density can be calculated from the expression  $n = A/(R_H e)$ , where  $e$  is the charge of the electron and  $A$  is proportional to the scattering constant  $r = \langle \tau^2 \rangle / \langle \tau \rangle^2$  and to a factor which comes from the nonspherical shape of the energy surfaces.

No reliable data are available on the concentration dependence of  $A$ . So we estimated the doping concentration  $N_D$  from  $\rho$  according to Irvin's curve<sup>13</sup> and calculated  $A = N_D R_H e$ , assuming total ionization of the impurities. We found that  $A$  increases from 1.3 at the doping concentration  $N_D = 10^{17} \text{ cm}^{-3}$  to 1.8 at approximately  $10^{18} \text{ cm}^{-3}$  and thereafter decreases to 1.1 at  $8 \times 10^{19} \text{ cm}^{-3}$  for *n*-type Si. Similar results were obtained for *p*-type Si. This behavior is roughly expected from theoretical considerations<sup>14</sup> and is qualitatively in good agreement with experimental results published by several authors.<sup>15,16</sup>

This shows that the carrier concentrations obtained from Hall measurements are consistent with the doping concentrations determined from Irvin's curve.

The results of the lifetime measurements for *p*-type Si are shown in Fig. 2, where the minority-carrier lifetime is plotted versus the impurity concentration. The different symbols characterize the measurements at 77, 300, and 400 K.

TABLE I. Auger coefficients for *e-e-h* and *e-h-h* process at different temperatures.

<i>T</i>	77 K	300 K	400 K
$C_n \text{ (cm}^6 \text{ s}^{-1}\text{)}$	$2.3 \times 10^{-31}$	$2.8 \times 10^{-31}$	$2.8 \times 10^{-31}$
$C_p \text{ (cm}^6 \text{ s}^{-1}\text{)}$	$7.8 \times 10^{-32}$	$9.9 \times 10^{-32}$	$1.2 \times 10^{-31}$

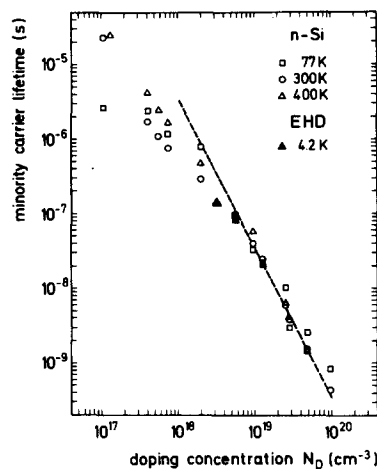


FIG. 3. Minority-carrier lifetime versus doping concentration in *n*-type silicon bulk material at 77, 300, and 400 K. The dashed line is the fit for 300 K and represents the quadratic dependence. The closed triangle shows the lifetime in the electron-hole drop (EHD) in pure Si after high excitation at 4.2 K.

For impurity concentrations higher than  $2 \times 10^{18} \text{ cm}^{-3}$ , the results can be well fitted by a *quadratic* dependence  $\tau \sim p^{-2}$ . The Auger rate constant at 300 K is found to be  $9.9 \times 10^{-32} \text{ cm}^6 \text{ s}^{-1}$ . Fitting the points at 77 and 400 K yields values which differ only slightly (see Table I).

In the lower doping range, lifetime is limited by a different recombination mechanism which is supposed to be Shockley-Read-Hall recombination.

The typical temperature dependence in this case is  $\tau \sim T^{-2}$ , which we, in fact, observe experimentally.

The Auger recombination for *n*-type Si is shown in Fig. 3. In this case, the lifetime is Auger-process limited at concentrations above  $6 \times 10^{18} \text{ cm}^{-3}$  which is larger than the corresponding concentration limit for *p*-type Si. The minority-carrier lifetime also decreases quadratically with increasing impurity concentration,  $\tau \sim n^{-2}$ . The Auger coefficient at 300 K for *n*-type Si is  $C_n = 2.8 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$ . Furthermore, we have investigated the Auger coefficient at different temperatures (77, 300, and 400 K). The results are given in Table I.

It should be pointed out that the Auger coefficient for *n*-type Si (*e-e-h*) is larger than for *p*-type Si. This is, in principle, expected on the basis of the band structure; however, one would expect a very much smaller coefficient for the *e-h-h* process in *p*-type Si.

The good quadratic dependence of lifetime versus doping concentration is in contrast to the results which Conradt and Aengenheister<sup>7</sup> experimentally obtained from germanium. They observed a  $p^{-1.5}$  dependence which, in a later paper,<sup>17</sup> was attributed to the dependence of the screening length on the carrier concentration.

Temperature dependence of the silicon Auger coefficients cannot be found explicitly in published theoretical treatments. For *p*-Ge, however, Huld<sup>18</sup> has calculated for a phonon-assisted Auger process that the

coefficient may slightly increase from the lowest temperatures to about 100 K, remain constant, and finally increase strongly above 300 K. Our results yield a notably weak temperature dependence for the silicon Auger coefficients which becomes still more remarkable when the results for highly doped Si are compared with those we obtained for highly excited Si at low temperatures. The main recombination mechanism in the electron-hole droplets (EHD) at low temperatures and high excitation is also assumed to be the Auger recombination.<sup>19</sup> Since the density of electrons and holes in the EHD is the same, the  $e$ - $e$ - $h$  as well as the  $e$ - $h$ - $h$  process occurs simultaneously. The equilibrium carrier density within the droplets is  $n_0 = 3.3 \times 10^{18} \text{ cm}^{-3}$ .<sup>20</sup>

We have measured the lifetime in the EHD and found a value of 137 ns,<sup>21</sup> which is also plotted in Fig. 3. From the density and this lifetime, an Auger coefficient of  $C = C_n + C_p = 1/(\tau n_0^2) = 6.7 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$  has been determined. The surprising result is that this is only slightly larger than for the high-doping case at much higher temperature,  $C_n + C_p = 3.8 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$ . For the  $e$ - $e$ - $h$  process in the EHD, the Auger coefficient  $C_n$  has already been obtained in a different way.<sup>22</sup> The value  $C_n = 1.5 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$  is consistent with the results reported here.

In conclusion, the Auger coefficients for  $e$ - $e$ - $h$  and  $e$ - $h$ - $h$  processes do not depend on the presence of impurities; they are similar, regardless of whether electrons and holes are generated by high doping or high excitation. Furthermore, they have little dependence on temperature in the range from 400 down to 4 K if the high-excitation results are included.

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## Method of separating hysteresis effects from MIS capacitance measurements

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A new method is proposed to estimate interface state density in hysteretic MIS devices. In this method, a narrow bias-voltage swing is applied around a certain center bias voltage to obtain a narrow  $C$ - $V$  curve without hysteresis. It is shown that the capacitance derivative obtained in this way depends on MIS capacitance only, and then can be used for determining the interface state density in the hysteretic InSb MIS devices.

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There are several methods to determine the interface state density in MIS devices. One of them was proposed by Terman<sup>1</sup> to estimate the density from capacitance measurements in a high-frequency region, where only charge carriers in the semiconductor can follow the

signal frequency. The interface state density  $N_{ss}$  may be calculated from this method and given by

$$N_{ss} = \frac{C_i}{q} \left( \frac{dC}{d\psi_s} \right)_{ideal} \left[ \left( \frac{dC}{dV} \right)^{-1} - \left( \frac{dC}{dV} \right)^{-1}_{ideal} \right], \quad (1)$$