J. Phys. C: Solid State Phys., Vol. 12, 1979. Printed in Great Britain. © 1979

Determination of the temperature dependence of the free carrier and interband absorption in silicon at 1·06 μm

K G Svantesson and N G Nilsson
Physics Department, Royal Institute of Technology, S-100 44 Stockholm, Sweden

Received 29 January 1979

Abstract. Simultaneous determinations of the free-carrier absorption cross-section, the interband absorption coefficient, and the surface reflectivity, at the Nd:YAG laser wavelength 1·06 μm and in the temperature interval 195–372 K are reported, using a method developed previously. The influence of the free-carrier absorption is described by an analytical model which fits the experimental data very well. The values of the interband absorption coefficient measured with short high-intensity laser pulses agree with the literature values measured at low intensity. The free-carrier absorption cross-section σ was found to be proportional to the absolute temperature, $\sigma = \sigma_n + \sigma_p = 1{\cdot}7 \times 10^{-20}\, T\,\mathrm{cm}^2$.

1. Introduction

In general, the absorption of photons in a pure semiconductor is associated with interband transitions across the forbidden gap and with free-carrier (intraband) absorption. One of these absorption processes usually dominates. The combination of silicon and a Nd laser at 1·06 μm is a rather special one, however, as the photon energy of the laser quite closely corresponds to the optical energy gap of silicon. As a consequence, the interband absorption coefficient is relatively low, and a pulsed Nd laser beam is useful for optical excitation of carriers in depth because of its wavelength, and for obtaining high concentrations of free carriers because of its intensity. With strong excitation a large number of electron–hole pairs is created, and the free-carrier absorption will become appreciable compared with the interband absorption. This will strongly influence the further creation of free carriers along the laser beam, and the total absorption of a laser pulse will become non-linear.

When carrier diffusion and recombination are negligible during the laser pulse the non-linear absorption can be described by an analytical model (Gauster and Bushnell 1970, Svantesson and Nilsson 1978a). This model agrees very well with measurements at room temperature. The free-carrier absorption cross-section can be determined without the use of a separate probe beam (Svantesson and Nilsson 1978a, Svantesson 1979). The measurements give the interband absorption coefficient α, the free-carrier absorption cross-section σ, and the surface reflectivity R, without the use of a literature value for any parameter. The measurement of σ relies on an area determination and a calorimetric measurement of the laser pulse energy.

This method has been used to determine the carrier concentration accurately in experiments on Auger recombination at room temperature (Svantesson and Nilsson 1979). In the present work we report measurements of the absorption, and an evaluation of the absorption parameters at temperatures below and above room temperature.

2. Theory

The model which describes the non-linear absorption of a short Nd laser pulse in Si has been treated in detail in previous papers (Svantesson and Nilsson 1978a, Svantesson 1979). The model shows that, when carrier recombination and diffusion in the direction of the beam are negligible during the pulse, the transmitted photon density $Q(x)$ is related to the incident photon density Q_0 by (Svantesson 1979, equation 20)

$$1/Q(x) = K/Q_0 + L + V. \tag{1}$$

The photon density of a pulse is defined as the total number of photons per unit area. The shape of the pulse is unessential. The constants K and L in (1) are related to the front surface reflectivity R, the interband absorption coefficient α, the sample thickness x, and the free-carrier absorption cross-section σ $(=\sigma_n + \sigma_p$, with equal concentrations of electrons and holes), according to

$$K = [\exp(\alpha x)]/(1 - R) \tag{2}$$

$$L = \tfrac{1}{2}\sigma[\exp(\alpha x) - 1]. \tag{3}$$

V in equation (1) is a small and slowly varying correction term which has been included in order to account for the effects of variations of the intensity across the laser beam (Svantesson 1979, equation 21). Such variations cannot be avoided because of diffraction effects behind the slit that defines the area of the beam. Q_0 and $Q(x)$ are the values obtained by averaging over the area of the beam at the sample. K and L can be obtained experimentally from measurements of $Q(x)$ with different Q_0.

Equations (2) and (3) show that L plotted versus K gives a straight line which yields $1/(1 - R)$ for $L = 0$, and $-\frac{1}{2}\sigma$ for $K = 0$, without a knowledge of the different values of x (two or more). On the other hand, if R has been determined from the measurements, σ can be computed from

$$\sigma = 2L/[(1 - R)K - 1] \tag{4}$$

for each sample thickness. The reflectivity R can be assumed to be independent of the laser intensity up to much higher levels than those used here (see for instance Blinov *et al* 1967, Auston *et al* 1978).

3. Experiments and evaluation

Samples were cut from a silicon ingot with a low impurity content, and polished with plane parallel surfaces. The rear surfaces were anti-reflection coated with a SiO layer. The samples were mounted on a rotatable holder on the cold (or warm) finger of a cryostat, and temperature sensors were mounted close to the samples. The temperature measurements were estimated to be accurate within ± 1 K, with a stability during measurements of about $\pm 0{\cdot}3$ K. The experimental arrangement and procedure previously described were used (Svantesson and Nilsson 1978a, Svantesson 1979), with excitation by a

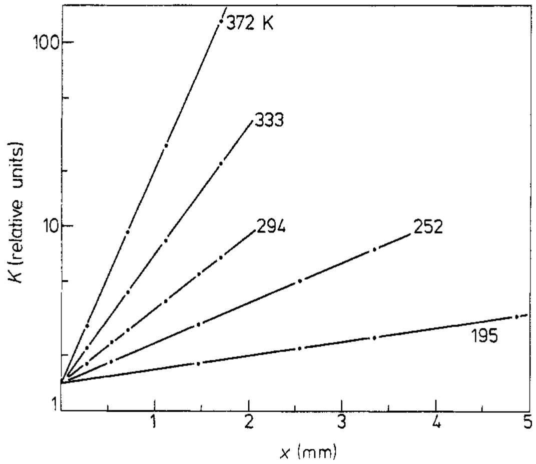

Figure 1. $K = [\exp(\alpha x)]/(1 - R)$ as a function of the sample thickness x plotted to determine α and R at the temperatures indicated. The full circles represent the measured values, and their size is approximately equal to the experimental accuracy.

Nd:YAG laser, giving up to 3×10^{18} photons cm^{-2} in single pulses of 15 ns FWHM. Measurements were made ten times and averaged for each combination of input intensity, thickness, and temperature. The calibration of the two photomultipliers which were used to measure Q_0 and $Q(x)$ was checked frequently. Thus the accuracy of the measurements was limited essentially by the calorimetric calibration of the multipliers also in the present series of experiments. A large number of measurements was required, and this is one reason why not all the available sample thicknesses were used at all temperatures.

One focusing lens was used ('many fringe' case), in the same geometry as before (Svantesson 1979). Thus the modulation factor $m = 0{\cdot}69$ determined then should be used in computing the correction term V in equation (1) also in the present work. The '$\cos^2 \varphi$' intensity distribution was considered unsuitable because of the lower value of the maximum photon density which could be achieved in that case.

Table 1. Measured values of the free-carrier cross-section σ for a number of sample thicknesses, the absorption coefficient α, and the reflectivity R, at various temperatures.

	Values of σ (in 10^{-18} cm^2) at T(k) =				
x	195	252	294	333	372
(mm)					
0·26			5.46	5·30	6·10
0·53		4·21	5·04		
0·71			5·05	5·76	6·39
1·10			5·27	5·78	5·97
1·46	3·38	4·52	4·67		
1·69			5·22	5·90	6·41
2·54	3·30	4·00			
3·34	3·50	4·26			
4·86	3·07				
σ_{av} (10^{-18} cm^2)	3·31	4·25	5·12	5·69	6·22
$\lvert\Delta\sigma\rvert_{\max}$($10^{-18}$ cm^2)	0·24	0·27	0·45	0·39	0·25
α (cm^{-1})	1·72	5·0	9·5	16·2	26·7
R (%)	29·1	29·6	30·1	29·6	31·0

The temperature range over which the experiments were performed was limited because at low temperatures α becomes so small that the concentration of free carriers was too low to cause appreciable free-carrier absorption, and because at high temperatures α becomes so large that accurate transmission measurements were not possible with the sample thicknesses available in our case.

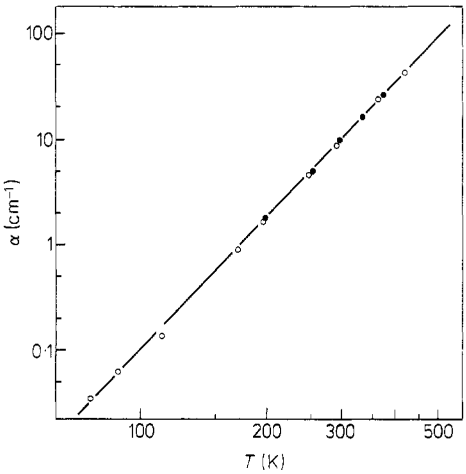

Figure 2. The temperature dependence of the absorption coefficient α at $\lambda = 1{\cdot}06\ \mu m$. Full circles: this work; open circles: data from Macfarlane *et al* (1958).

Equation (1) shows that $1/Q(x)$ is a linear function of $1/Q_0$ (Svantesson 1979). A fit of a straight line to a plot of $1/Q(x)$ versus $1/Q_0$ gives preliminary values of K and L, which in turn yield α and R, as well as an effective cross-section σ_{eff}. A preliminary value for σ can then be computed from σ_{eff} (Svantesson 1979, equation 24). With these starting values, and the modulation factor $m = 0{\cdot}69$, the correction term V was computed (Svantesson 1979, equation 21) for each value of Q_0. $1/Q(x) - V$ was plotted versus $1/Q_0$, giving straight lines and final values for K and L (further iterations were not necessary). A plot of $\lg(K)$ versus x yields α from the slope of the fitted straight line, and R from the intercept at $x = 0$. This is illustrated in figure 1 for the various temperatures. The results at 294 K are those published earlier (Svantesson 1979, where figure 2*b* shows the uncorrected data). The resulting values of α and R are given in table 1. The accuracies of the α values, which are obtained from relative measurements only, are estimated to be better than $\pm 2\%$.

The temperature dependence of the reflectivity R is weak, which is consistent with literature data for the refractive index (Lukeš 1959). In our opinion, the accuracy of our determination does not warrant further analysis.

The values of the absorption coefficient α obtained in this work are in excellent agreement with the classical literature values (Macfarlane *et al* 1958), which were measured at low light intensity. This is illustrated in figure 2, which is a plot of $\lg(\alpha)$ versus $\lg(T)$. The diagram shows that the temperature dependence of α can be described by a power law:

$$\alpha(T) = [T/172{\cdot}3]^{4{\cdot}25}\ \mathrm{cm^{-1}}, \qquad \text{at } \lambda = 1{\cdot}064\ \mu m. \tag{5}$$

The line in figure 2 represents the relation (5).

It has been shown (Svantesson 1979) that determinations of R from $\lg(K)$ versus x or from L versus K give almost identical results. As only four thicknesses were measured at most temperatures in the present experiments, a plot of L versus K is not suitable for the determination of σ. Instead, the values of R obtained from the fit in figure 1 at each temperature, and the K and L values for each thickness, have been used to calculate σ from equation (4). The results for the different values of x and T are given in table 1. This table also shows the average values σ_{av} and the maximum deviation from the average. Each value of σ_{av} is based on at least 450 readings of Q_0, $Q(x)$ combinations.

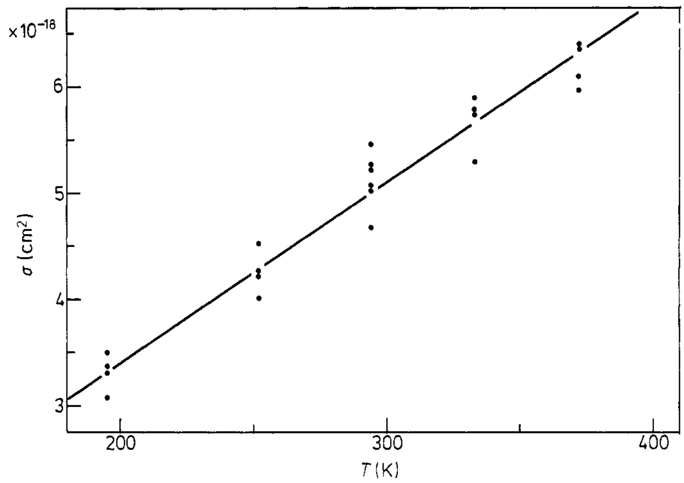

Figure 3. The free-carrier absorption cross-section σ as a function of the temperature. The points represent the experimental results (table 1). The line is a least-squares fit to the points. Within the accuracy of the fit, it starts at ($T = 0$; $\sigma = 0$).

The temperature dependence of σ is shown in figure 3 (the data of table 1). A straight line fitted to the experimental points passes through $\sigma = -0{\cdot}5 \times 10^{-18}\ \mathrm{cm}^2$ for $T = 0$, showing that σ is proportional to T, within the accuracy of the experiments. Such a temperature dependence is characteristic of absorption associated with acoustical phonon scattering (see for instance Seeger 1973), and there is no evidence for scattering by ionised impurities, which has been seen at longer wavelengths (Huldt and Staflin 1961a, b).

The line in figure 3 represents the fitted expression

$$\sigma(T) = 1{\cdot}7 \times 10^{-20}\ T\ \mathrm{cm}^2, \qquad \lambda = 1{\cdot}604\ \mu\mathrm{m}. \tag{6}$$

The standard deviation of the coefficient, computed from table 1, is approximately 5 %. In addition, the 3 % accuracy specified for the Scientech energy meter used for calibration, and the statistical errors in the calibration procedure, must be taken into account. Then the resulting total uncertainty will be less than 7 % in the expression (6) for $\sigma(T)$ in the temperature interval 195–372 K. The temperature dependence is different from that which has been obtained in doped silicon at longer wavelengths (Schroder *et al* 1978).

4. Conclusions

The absorption model, which has been applied to interpret the experiments, has proved to fit the measured pulse transmission data very well for all the values of temperature, sample thickness, and input intensity used. We conclude that the strongly non-linear absorption of photons at the Nd:YAG laser wavelength can be accurately described by a constant interband absorption coefficient α, equal to the value measured at low intensities, and a constant free-carrier absorption cross-section σ, which is independent of the carrier concentration. No evidence for saturation of the free-carrier absorption (Gibson *et al* 1972) was seen. The intraband transitions cause a non-linear absorption effect, which must be considered when a Nd laser is used to create free carriers in silicon.

The free-carrier absorption may also cause heating of the sample (Svantesson and Nilsson 1978a). In the present experiments, however, the intensity has been kept sufficiently low to avoid recombination during the laser pulse, and the heating was therefore negligible. Because of the simple temperature dependences of α and σ, as shown in equations (5) and (6), a simple analytical model can be constructed for the heating of the sample at higher laser intensities. This will be discussed separately.

Acknowledgments

This work was supported by the Swedish Natural Science Research Council.

References

Auston D H, Surko C M, Venkatesan T N C, Slusher R E and Golovchenko J A 1978 *Appl. Phys. Lett.* **33** 437

Blinov L M, Vavilov V S and Galkin G N 1967 *Fiz. Tverd. Tela* **9** 854 (1967 *Sov. Phys.–Solid St.* **9** 666)

Gauster W B and Bushnell J C 1970 *J. Appl. Phys.* **41** 3850

Gibson A F, Rosito C A, Raffo C A, and Kimmitt M F 1972 *Appl. Phys. Lett.* **21** 356

Huldt L and Staflin T 1961a *Proc. Int. Conf. Semiconductor Physics, Prague 1960* (Prague: Czech Acad. Sci.) p 385

—— 1961b *Ark. Fys.* **20** 527

Lukeš F 1959 *J. Phys. Chem. Solids* **11** 342

MacFarlane G G, McLean T P, Quarrington J E and Roberts V 1958 *Phys. Rev.* **111** 1245

Schroder D K, Thomas R N and Swartz J C 1978 *IEEE Trans. Electron. Dev.* **ED-25** 254

Seeger K 1973 *Semiconductor Physics* (Vienna and New York: Springer-Verlag) 11*j*.

Svantesson K G 1979 *J. Phys. D: Appl. Phys.* **12** 425

Svantesson K G and Nilsson N G 1978a *Phys. Scripta* **18** 405

—— 1978b *Solid St. Electron,* **21** 1603