Time-Resolved Reflectivity Measurements in Silicon

In a recent Letter,[1] Shank, Yen, and Hirlimann (SYH) report experiments on time-resolved reflectivity of laser-irradiated silicon using femtosecond pulses. We show that SYH have overestimated by one order of magnitude the value of the density of electron-hole pairs produced in their experiments, and that *their conclusion on the absence of Auger recombination is thus incorrect.* In addition, we believe that these experiments give a good evidence for plasma-assisted melting.[2]

To estimate the density N_p of electron-hole pairs, SYH use the formula $\omega_p^2 = 4\pi e^2 N_p / m^* \epsilon_c$ for the plasma frequency ω_p and choose the value $m^* = m_0$ (the free-electron mass). With this value, they find $N_p = 5\times 10^{21}$ cm^{-3} at a laser incident energy $E = 6.3\times 10^{-2}$ J cm^{-2}. We show that the correct value of the plasma reduced effective mass in these experimental conditions is $\mu = 0.12 m_0$ leading to a value of $N_p = 6\times 10^{20}$ cm^{-3}. For a plasma containing N_e electrons and N_h holes, ω_p is given by

$$\omega_p^2 = \frac{4\pi e^2}{\epsilon_c}\left[\frac{N_e}{m_e} + \frac{N_h}{m_h}\right].$$

When $N_e = N_h = N_p$, we have $\omega_p^2 = 4\pi e^2 N_p/\epsilon_c \mu$ with $\mu^{-1} = m_e^{-1} + m_h^{-1}$. In the case of silicon and at moderate densities, μ is given by[3]

$$\frac{1}{\mu} = \frac{1}{3}\left(\frac{1}{m_\parallel} + \frac{2}{m_\perp}\right) + \frac{1}{2}\left(\frac{1}{m_H} + \frac{1}{m_L}\right),$$

where $m_\parallel$ and $m_\perp$ are the longitudinal and transverse electron masses and m_H and m_L the heavy and light hole masses, and thus $\mu = 0.12 m_0$. The important point is to determine how μ varies at high densities. μ has been measured by Miyao *et al.*[4] in N-doped silicon ($N_h = 0$) up to $N_e = 5\times 10^{21}$ cm^{-3}. They obtain a constant value of $0.28 m_0$ for $N_e \leqslant 10^{21}$ cm^{-3} and an increase by a factor 2 at $N_e = 5\times 10^{21}$ cm^{-3}. With $N_h = 0$, we find $\mu = m_e = 0.26 m_0$ in very good agreement with the experimental value. In the experiments of SYH, the plasma consists of electron-hole pairs, and the correct value is thus $\mu = 0.12 m_0$ for $N_p = 5\times 10^{21}$ cm^{-3}. Moreover, Si band structure was calculated by Chelikowsky and Cohen.[5] Their results indicate that the carrier concentration at which the Fermi level enters an upper valley is 5×10^{20} cm^{-3}, consistent with the experiments of Miyao *et al.* We obtain an independent check of the maximum value of N_p by simply assuming that each absorbed photon gives one electron-hole pair, neglecting recombination and expansion in 90 fsec. Using an absorption length, given by SYH, of $d = 3$ μm, we find $N_p = 4\times 10^{20}$ cm^{-3}. d is probably slightly decreased by free-carrier absorption and nonlinear effects, this explaining that N_p is actually slightly larger.

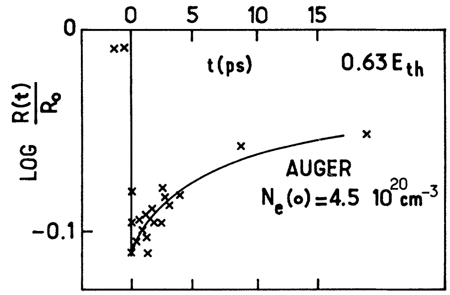

FIG. 1. Reflectivity vs time. Solid line, calculated values based on Auger recombination. Crosses, experimental points from Ref. 1.

The second independent check comes from the fact that our value of N_p nicely explains the decay of reflectivity observed by SYH in terms of Auger recombination. Figure 1 shows the comparison of the calculated variation of $\log \boldsymbol{R}(t)/\boldsymbol{R}_0$ vs t, with use of Auger recombination and initial density $N_e(0) = N_h(0) = 4.5\times 10^{20}$ cm^{-3}, with SYH's experiments. The agreement is excellent.

Finally, we think that the experiments of SYH show evidence for plasma-assisted melting. Assuming that all the laser energy at E_h is transformed into heat, we find that the maximum temperature reached at the surface of the silicon sample is much less than the melting temperature. Using the reflectivity data of SYH, we find a density N_p in the range where the instability induced by the electron-phonon interaction was predicted.[2]

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