Comment on the "Evidence for a Self-Confined Plasma" in Laser Annealing

Aydinli, Lo, Lee, and Compaan[1] (ALLC) report the spectral dependence of the induced absorption of silicon on sapphire under intense laser illumination. They claim that these results are due to the existence of an electron-hole plasma with a density of 4×10^{22} cm^{-3}, providing evidence for the self-confined plasma predicted by Van Vechten and Wautelet.[2] We think that this conclusion is erroneous for the following reasons:

(1) The optical properties of an *e-h* plasma with densities of the order of 4×10^{22} cm^{-3} do not fit at all the experimental results. The study[3] of *e-h* droplets in Si gives the average energy, for $T \ll T_F$ the Fermi temperature, $\epsilon \simeq 5.3\times10^{-12}n^{2/3} - 11.2\times10^{-6}n^{1/3}$ where ϵ is in meV and n in cm^{-3} (the correlation energy being negligible at large n). So for $n=4\times10^{22}$ cm^{-3}, $\epsilon = 6.2$ eV, $E_F{}^e + E_F{}^h \simeq 10$ eV!! (if one assumes the same effective mass) and $T_F \sim 60\,000$ K which means that the plasma is cold even at the melting point. The resulting "optical gap" or threshold energy for band-to-band absorption should be at $E_0 = 11.5$ eV, in contradiction with the observed absorption which shows little shift compared to the one of Si with no excess *e-h* pairs. For 1.3 eV $< h\nu <$ 3.3 eV $\ll E_0$ the optical properties of such a dense plasma should be that of a metal.

(2) Our second point concerns the possibility of forming a 4×10^{22} cm^{-3} plasma which is confined in 0.07 μm and which lasts the 70 nsec during which the high reflectivity is seen. The key point for the self-confinement found by Van Vechten and Wautelet rests on the hypothesis that in a dense plasma the electron-phonon interaction has disappeared as well as the Auger recombination. One usually believes that the *e-h* lifetime decreases with density as $(Cn^2)^{-1}$, with $C = 4\times10^{-31}$ cm^6 s^{-1} in Si, and saturates for $n > 10^{21}$ cm^{-3} at $\tau_0 \sim 6\times10^{-12}$ s because of screening. ALLC's pulse ($W = 1$ J cm^{-2}, $\lambda = 485$ nm, $\tau = 8$ nsec) creates $F = 3.1\times10^{26}$ photons cm^{-2} s^{-1} (if one forgets the reflectivity). The maximum density in the confined region extending over $D = 0.07$ μm verifies $F/D - Cn^3 = 0$, i.e., $n = 5\times10^{20}$ cm^{-3}, much lower than the value of 4×20^{22} cm^{-3} quoted by the authors. (Note that this density does not vary very much with D.)

Moreover, a 4×10^{22}-cm^{-3} plasma can never last 70 ns. After the pulse, the time evolution of the plasma density is ruled by $dn/dt = -n/\tau(n)$, where $\tau(n) \sim \tau_0 + 1/Cn$. So the density decreases from n_i to n in a time t given by

$$t = \tau_0 \ln\frac{n_i}{n} + \frac{1}{2Cn_i{}^2}\left(\frac{n_i{}^2}{n^2} - 1\right);$$

starting from $n_i = 4\times10^{22}$ cm^{-3}, $n = 4\times10^{20}$ cm^{-3} at $t = 35$ ps and $n = 5\times10^{18}$ cm^{-3} 70 nsec after the pulse! As we believe that electron-phonon interaction and Auger recombination exist, we[4] cannot understand an *e-h* plasma density of 4×10^{22} cm^{-3} lasting 70 ns.

(3) Finally, the crystalline phase of covalent Si is no longer the thermodynamically stable phase of Si when the density of *e-h* is greater than 8×10^{21} cm^{-3} at 0 K. Heine and Van Vechten[5] have shown that at such a density the transverse-acoustic modes go to zero frequency and the crystal becomes liquid at 0 K. For higher temperature one of us (J.B.)[6] has estimated the critical density n_p for the melting of silicon. At 600 K, $n_p = 3\times10^{21}$ cm^{-3}. So at 4×10^{22} cm^{-3}, the stable phase is the liquid one.

In summary, we think that the experimental optical properties reported by the authors are not due to a dense *e-h* plasma for three main reasons. The absorption of a plasma with a density of 4×10^{22} cm^{-3} is that of a metal with a Fermi energy of 10 eV; such a high-density plasma cannot exist during 70 ns because of Auger recombination; and at densities higher than 8×10^{21} cm^{-3}, the thermodynamically stable phase is the liquid one.

J. Bok
M. Combescot
Groupe de Physique des Solides de l'École
Normale Supérieure
F-75005 Paris, France

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[2] J. A. Van Vechten and M. Wautelet, Phys. Rev. B 23, 5543 (1981).

[3] See, for example, M. Combescot and P. Nozières, J. Phys. C 5, 2369 (1972).

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[5] V. Heine and J. A. Van Vechten, Phys. Rev. B 13, 1622 (1976).

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