

justified as long as the Larmor frequency (and the rf field frequency) is small compared to the gap.

To summarize, we have shown that a transverse rf field will induce transitions between the modes of a collective-mode multiplet in $^3\text{He-B}$ and that these transitions will lead to modifications in the zero-sound propagation which can be in some cases very important. We believe that this kind of experiment should provide a very powerful tool in the detailed study of the collective modes, and therefore in the knowledge of the Cooper pair structure in $^3\text{He-B}$.

Finally, we note that, in order to exhibit the simplest physical picture, we have deliberately omitted some complicating features. First the equations¹¹ ruling the coupling between zero sound and the squashing mode are actually more complicated than Eq. (7). We have also neglected the dispersion of the various modes of a multiplet which gives rise to an additional splitting at $q \neq 0$. This will in general produce unequal spacing between the levels. In some cases this will be negligible (high static magnetic field, strong damping). But this problem can also be overcome by the use of two (or more) radio-frequency fields. There is also the possibility of exciting more than one mode by the sound wave and conversely of detecting the rf-excited mode by its associated sound wave. In all these cases we expect quantitative changes, but the basic phys-

ical picture should remain the same.

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Investigation of the Melting Temperature of Amorphous Silicon

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Time-resolved optical reflectivity measurements were used to investigate phase changes which occur in silicon during cw-laser heating. It is shown that amorphous silicon does not melt at a temperature significantly lower than the melting point of crystalline silicon (1693 K), contrary to recent reports which suggested a 300- to 500-K melting-point depression.

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It has recently been suggested^{1,2} that the melting temperature of amorphous silicon is considerably lower than that of the crystalline material. On the basis of the assumptions that the free energy of the amorphous state is higher than that of the crystal near the melting point and that there is a first-order transition between the amorphous and

the liquid phases, Bagley and Chen¹ predicted that amorphous silicon would melt at 1349 K, more than 300 K lower than the melting temperature of crystalline silicon. Using data from pulsed-electron-beam heating experiments, Baeri *et al.*² subsequently deduced a melting temperature of 1170 ± 100 K for thin silicon films made amor-

phous by ion implantation. In contrast, using cw-laser heating, we have observed³ *solid-phase* crystallization of amorphous silicon at temperatures considerably in excess of the melting temperatures reported by Baeri *et al.* and estimated by Bagley and Chen. Similar observations from scanned-electron-beam heating experiments were reported by Knapp and Picraux.⁴ The absence of melting at temperatures above 1349 K in the latter two studies prompted us to investigate the suggested melting-point reduction in greater detail. We have used a time-resolved optical reflectivity technique^{3,5} to monitor phase changes which occur during cw-laser heating and have refined the technique to allow determination of temperature during rapid crystallization and melting. We have found that amorphous silicon can be raised to temperatures greater than 1600 K without melting.

The reflectivity measurements reported here were performed during cw-laser heating of thin amorphous Si layers produced by ion implantation of crystalline substrates. Wafers of *p*-type Si(100) (1–10 Ω cm; 310 μ m thick) were implanted with arsenic (5×10^{14} cm⁻²; 158 keV) to form an amorphous film approximately 1600 Å thick. Samples from these wafers were then irradiated by a cw argon ion laser having a beam radius (at 1/e intensity) of 80 μ m at incident laser powers ranging from 14 to 23 W. The samples were exposed to the beam by using a mechanical shutter which opened completely in 10 μ sec. During irradiation the wafers were maintained at a constant bias temperature on a resistively heated stage. The reflectivity at the center of the heated spot was monitored using a 5-mW HeNe laser with a beam radius (at 1/e intensity) of 7 μ m.

Measurement of the reflectivity during cw-laser heating of silicon gives direct information about its physical state or phase because the reflectivities of crystalline, amorphous, and liquid silicon at 6328 Å have distinct values, and in particular, because there is a large increase in reflectivity upon melting. Moreover, the reflectivity also provides a convenient measure of temperature because it increases nearly linearly with temperature in the solid state.⁶ These effects are illustrated in Fig. 1 by time-resolved reflectivity data taken at five different argon laser powers. In each case the initial reflectivity of the amorphous silicon sample is 0.44 at the substrate temperature of 770 K. During the first 100 to 200 μ sec of laser heating the reflectivity increases rapidly as the temperature rises. This is fol-

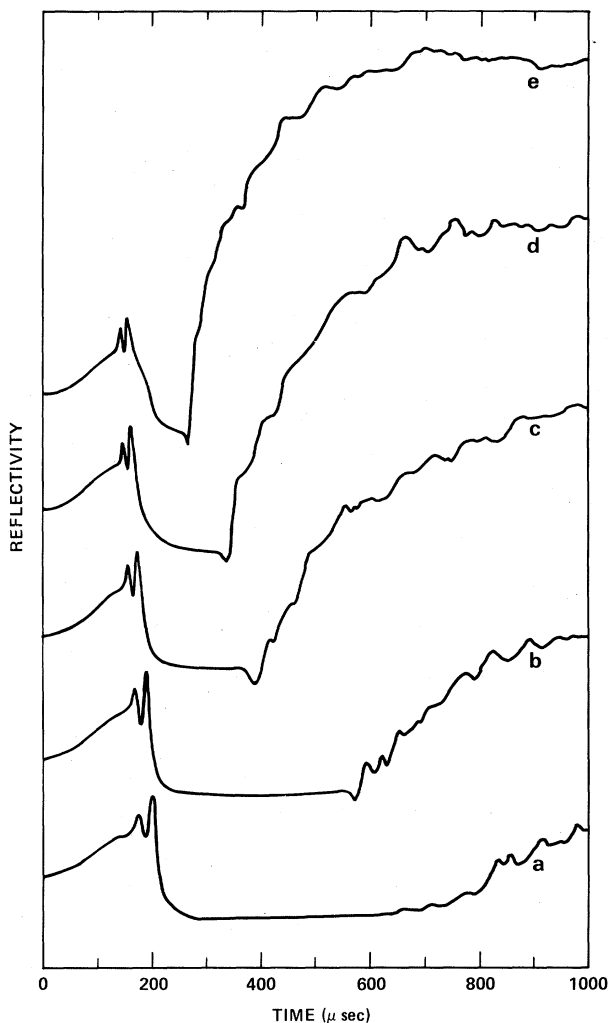


FIG. 1. Reflectivity (at 6328 Å) of ion-implanted Si(100) during cw laser irradiation at five different powers: a, 14.1; b, 15.0; c, 16.0; d, 16.9; and e, 18.3 W.

lowed by solid-phase epitaxial (SPE) crystallization of the amorphous film as evidenced by reflectivity oscillations which are caused by optical interference between light reflected from the surface and light reflected from the advancing epitaxial growth interface beneath the surface.^{3,5} Upon completion of solid-phase crystallization the reflectivity decreases to about 0.40, characteristic of single-crystal silicon at high temperature. This is followed by a marked increase in reflectivity when the surface of the sample begins to melt. As the laser power is increased, the time interval between completion of crystallization and the onset of melting decreases, indicating that the melting temperature is reached sooner at

higher powers. The final reflectivity reaches a higher value at higher powers because of the increased thickness of the molten layer. The latter effect has been studied in detail⁷ and can be understood in terms of optical interference effects produced by a thin melted layer. The maximum final reflectivity observed at the highest laser powers used in this study is about 0.75, comparable to the reported reflectivity of liquid silicon.⁸

In order to determine the temperature of the amorphous film during crystallization, we have carefully measured the transient reflectivity response of crystalline silicon during cw laser heating. The use of a single-crystal sample for temperature determination is justified because the thermal response of a thin amorphous surface layer, which forms about 5×10^{-4} of the total sample thickness in ion-implanted samples, is totally dominated by the thermal properties of the substrate and is essentially identical to the response of a single-crystal sample on the time scale of these experiments. Since the single-crystal reflectivity at 6328 Å increases linearly with temperature,⁶ the reflectivity measured as a

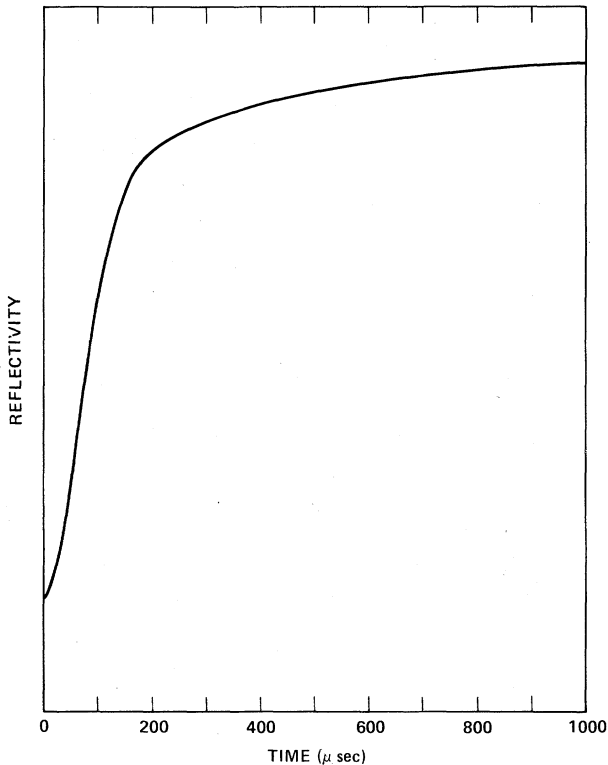


FIG. 2. Time-dependent reflectivity (at 6328 Å) of single-crystal silicon upon exposure to a cw argon laser beam.

function of time provides a signal that is directly proportional to the sample temperature. The basic reflectivity versus time data is given in Fig. 2; this curve represents the normalized reflectivity response and is valid for all laser powers used in this study. The method used to deduce the sample temperature as a function of time from the reflectivity transient is given below.

In Fig. 3 we present reflectivity data similar to those of Fig. 1, but obtained at a laser power of 22.6 W and displayed on expanded time and amplitude scales. We define the SPE growth temperature T_g as the temperature of the amorphous film at the time t_g during SPE growth when the reflectivity reaches the last local minimum. This operational definition of the growth temperature is used because the temperature increases during the entire growth time. It can be shown by optical thin-film analysis⁹ that the remaining amorphous film thickness at the time t_g and temperature T_g is about 600 Å. We identify the temperature at time t_m , when the reflectivity increases sharply, as the single-crystal melting temperature, 1693 K.¹⁰ Since the normalized thermal response is given by the single-crystal reflectivity data of Fig. 2, knowledge of the initial temperature (770 K) and the melt value at time t_m supplies the

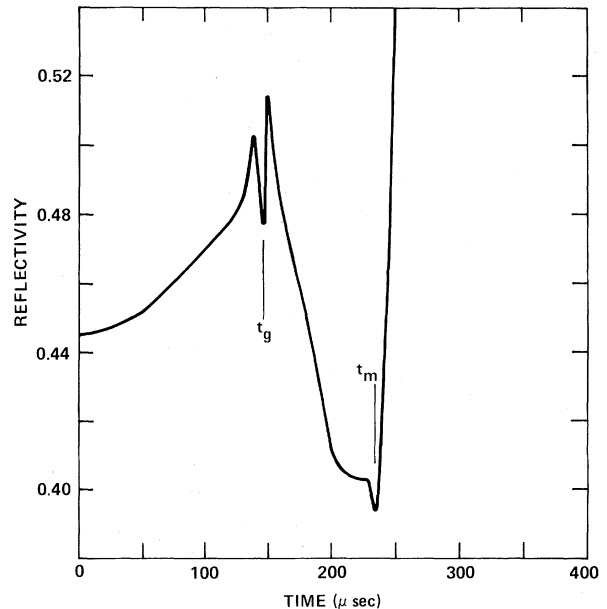


FIG. 3. Reflectivity (at 6328 Å) of ion-implanted Si(100) during cw argon laser heating at an incident power of 22.6 W. At time t_g , 600 Å of amorphous material remains; melting begins at time t_m . The epitaxial crystallization is 1.14 cm/sec during the time interval immediately following t_g .

necessary information needed to determine the temperature at any other time, and in particular at time t_g . We have determined that T_g is 1608 K, and that the temperature at the completion of SPE growth is 1654 K. Therefore the 600-Å amorphous film remaining after time t_g crystallized by a solid-phase process while its temperature was raised to within 39 K of the crystal melting point and there was no indication of melting.

The experimental conditions in the cw-laser heating process are very conducive to observing a lower amorphous melting temperature if it exists, because the amorphous material is quickly heated to temperatures very close to the crystalline melting point, and remains at these temperatures for several microseconds. The heating duration is important because a finite time period is required for the phase transition to occur. An upper limit on the time required to produce a solid-to-liquid phase transition can be inferred from pulsed-laser annealing experiments, where enough energy to melt several thousand angstroms of an amorphous silicon surface layer is typically deposited within a few nanoseconds. In a number of such experiments¹¹ complete melting and recrystallization have been reported to occur within time intervals much shorter than a microsecond. A second consideration for melting the amorphous layer is the rate of energy deposition relative to the rate of SPE growth. At 5×10^4 W/cm², the highest laser flux used in our study, the latent heat required to melt a 600-Å layer of silicon is deposited in about 0.5 μsec, a time much shorter than the epitaxial growth time. Thus both the energy deposition rate and the intrinsic melting rate are fast enough to allow the phase transition to occur during cw-laser heating experiments. This is evident from the data in Figs. 1 and 3 where melting of crystalline material is clearly observable on a time scale of a few microseconds.

On the basis of the data and analysis presented in this Letter it is our conclusion that amorphous silicon does not melt at a temperature significantly lower than the melting point of crystalline silicon. We have found no evidence to support the contention by Baeri *et al.*² that there is a difference of several hundred degrees between the melting points of these two forms of silicon. In their pulsed-electron-beam experiments the ob-

servations of poor-quality epitaxy was used as an indicator of melting despite the fact that it occurred at a beam fluence significantly less than the threshold fluence for redistribution of implanted marker atoms. In view of our results and the inordinately high crystallization rates which would be required to explain the lack of marker-atom redistribution, we believe that the observation of poor-quality epitaxy is not necessarily a valid criterion for melting. A detailed discussion of this point along with an alternate interpretation of the electron-beam experiments which resolves the contradiction with the present work will be given elsewhere.¹²

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