Measurement of Lattice Temperature of Silicon during Pulsed Laser Annealing

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and

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A classical time-of-flight method was used to determine the temperature of evaporated Si atoms and thus the lattice temperature of Si during pulsed laser annealing. The resulting temperatures between 1200 and 3000 K for energy densities between 1.0 and 2.5 J/cm^2 clearly support a strictly thermal annealing model including melting of the surface region of Si.

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During the last three years pulsed laser annealing of doped Si has proven to become a valuable alternative to oven annealing.[1] The promising results for semiconductor applications led almost to an explosion in the amount of research in this field.[2] However, despite the large number of papers the microscopic processes taking place inside the Si as a result of the laser pulse are still unclear. In principle there are two basically different models for them: a strictly thermal model and an alternative non–thermal-equilibrium model. Most experimental and theoretical papers favor the thermal model, under the assumption that the surface of Si melts for about 100 nsec as a result of the commonly used 20-nsec laser pulse of energy density of ~ 1.5 J/cm^2. This thermal model[3] can explain unambiguously the advantages of Q-switched laser annealing such as annealing of lattice damage after ion implantation or recrystallizing amorphous films or enhancing the dopant solubility. However, the nonthermal model is also able to give alternative, more sophisticated explanations for the experimental observations. This non–thermal-equilibrium model[4] emphasizes that the laser energy is transformed into highly excited carriers. This hot plasma is assumed to carry away the laser energy out of the surface region into the bulk so fast that the Si lattice itself remains rather cold. This theory was recently supported by Raman measurements[5] yielding lattice temperatures of Si as low as 300 °C for a laser pulse of ~ 1 J/cm^2. This experiment used very small spot sizes (diameter $\approx$ 50 μm) for both high power and analyzing laser which were difficult to adjust.

We report here measurements of the lattice temperature of Si during a widespread laser pulse with use of a classical time-of-flight method.[6] This method allows us to determine the energy and thus the temperature of Si atoms which are evaporated from the hot Si surface according to its vapor pressure. We find lattice temperatures between 1200 and 3000 K for pulse energies between 1.0 and 2.5 J/cm^2. This result shows clearly that Si is in the molten state during laser annealing (Si melting point $\simeq$ 1680 K) for energy densities $\geq$ 1.4 J/cm^2.

The Si single crystal (110) was mounted in a target holder rotatable around the axis of a bakable UHV system as shown schematically in Fig. 1. The surface of the Si can be analyzed with a cylindrical Auger analyzer in one rotary position. In the second measuring position the Si target is normal to a Q-switched ruby laser beam. The energy density of the laser can be varied by using different absorption plates and/or different positions of the focusing lens. A fixed fraction of the energy of each laser pulse is reflected from the surface of a glass plate into a light-sensitive diode. This signal has been calibrated against a

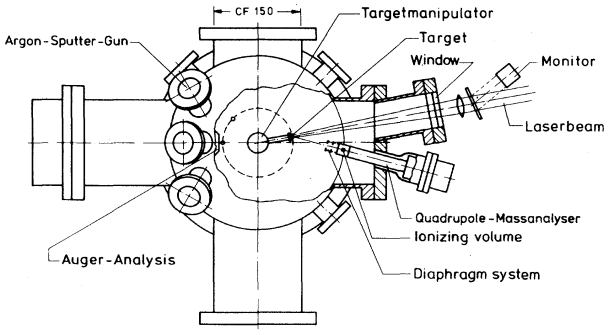

FIG. 1. Schematic of the experimental setup.

calorimeter which had been put in the sample position. The diameter of the laser beam was measured from the burned area of a Polaroid film as a function of the lens position. These calibrations allow the determination of the energy density within 10% for each laser pulse. The other components of the experimental arrangement have been described elsewhere.[7]

In this second position a quadrupole mass spectrometer (QMS) can analyze the atoms ejected from the Si target. The distance between the target and the ionization chamber of the QMS amounts to $l = 9$ cm. Atoms which are evaporated from the Si target as a result of the laser energy will move with thermal velocity to the ionization volume of the QMS. After ionization they are accelerated by an electric field and need 14 μsec (for mass 28) to be detected by the photomultiplier. The total time required between laser pulse and detection can be determined by sampling the QMS signal versus time with a fast dual-beam oscilloscope which is triggered shortly before the Q switch of the laser. The second trace of the oscilloscope is used to measure the corresponding laser energy. A typical example is shown in the photograph of Fig. 2. Trace A shows the inverse plot of the number of Si atoms detected with the QMS versus time. Trace B is the integrated signal of the laser-power–detecting diode and thus the laser energy as a function of time (time scales different for both traces).

In order to evaluate the temperature from the observed response of the QMS we must consider the classical evaporation process. The velocity distribution of atoms from a hot surface is of the Maxwell type, i.e., the number n of atoms moving with velocity v is given by the expression

$$dn = c_1 n v^3 \exp[-(v/v_0)^2]\,dv,$$

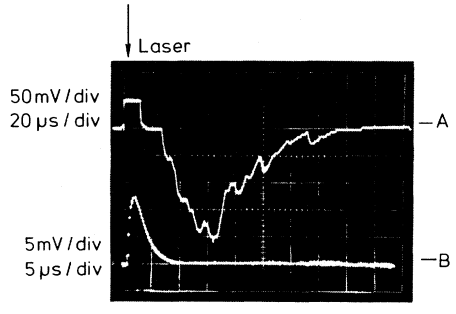

FIG. 2. Photograph of both the QMS signal (inverse) and the laser power as a function of time (different time scales).

with $v_0^2 = 2kT/m$ the most probable velocity, and constant c_1. These atoms reach the ionization volume of the QMS after passing the distance $l = 9$ cm and the arrival times are measured. Therefore we have to convolute the Maxwellian distribution into a time distribution. This is done by using $v = l/t$. In addition we have to take into account that the detection probability is proportional to the time the atoms are within the ionizing volume. Therefore the Maxwellian distribution has to be multiplied by $1/v$. These transformations result in the distribution function $f(t)$:

$$f(t) = n^{-1} dn/dt = ct^{-4} \exp[-(t_0/t)^2].$$

In order to evaluate the temperature T we determine the time t_{max} when the maximum of $f(t)$ has reached the QMS:

$$t_{max} = 1/\sqrt{2}\,t_0 = \tfrac{1}{2}(m/kT)^{1/2};$$

then

$$T = (l^2 m/4k) t_{max}^{-2}.$$

It should be emphasized that these considerations are valid as long as the time interval for emission of atoms is short compared to their time of flight.[8] This prediction is well fulfilled in our case: emission during the laser pulse ~ 50 nsec << (time of flight) ~ 50 μsec.

The experiment was performed after bakeout of the UHV chamber at 2×10^{-10} mbar. About ten

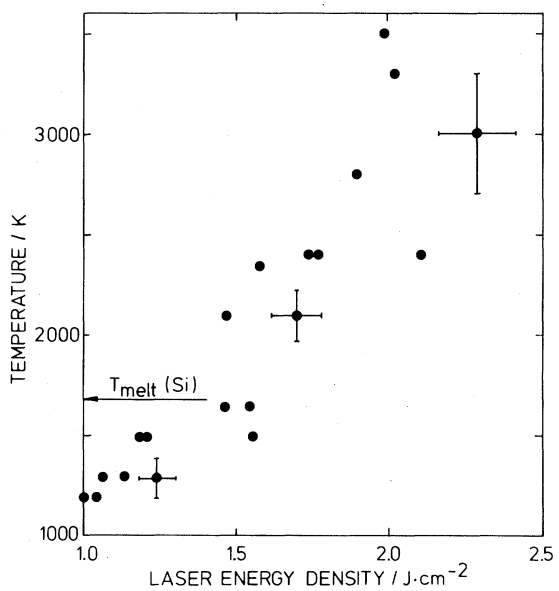

FIG. 3. Temperature of Si as a function of energy density of a Q-switched ruby laser.

laser pulses were used to clean the Si surface.[9] By Auger analysis no oxygen and nearly no carbon (< 1.8%) could be detected. Then the Si target was exposed to different definite laser energies and the corresponding distribution function $f(t)$ was measured with the QMS. The resulting values for t_{max} could be determined with an accuracy of ± 2.5 μsec. Then the resulting temperature was calculated. Figure 3 shows the temperature as a function of the corresponding laser energy density. A reliable signal $f(t)$ could only be determined for laser energy densities ≥ 1.0 J/cm^2, yielding Si temperatures of 1200 K. At this temperature Si has a vapor pressure of $\sim 10^{-8}$ mbar resulting in $\sim 10^{-11}$ mbar in the ionization volume. This pressure is just the sensitivity limit of the QMS, which was already found in earlier measurements on Ni targets.[6,7] The QMS signal increases very strongly with temperature as a result of exponential increase of the vapor pressure, and even saturates the detection system above 2300 K. In this case t_{max} is determined as the midpoint of the flat, saturated signal. At these high energy densities very often a substantial part of the evaporated atoms is ionized, giving rise to a strong QMS signal within the first 5 μsec. With increasing laser energy density the lattice temperature of the Si target increases nearly linearly to about 3000 K at 2.5 J/cm^2. An exact analytical expression for T as a function of the laser energy could not be determined because of the rather large errors in both energy density and temperature. This is also the reason that no discontinuity in T around the melting point T_{melt} could be observed, which could be expected since the heat of melting has to be applied.

These reported measurements of the Si lattice temperature during pulsed laser annealing show clearly that Si is molten during the commonly used energy densities of 1.5–2.0 J/cm^2. Thus clearly the thermal theories give the adequate description of the laser annealing process[3]; we have no hint of support for the non-thermal-equilibrium theory.[4] Our result is completely different from the temperature determination by Raman scattering. We guess that the discrepancy is due to the difficulties in the Raman experiments caused by the small laser beam spots with respect to both adjustment and energy density determination. In contrast the present experiment uses large beam spots (diameter $\simeq 5$ mm) and a time-of-flight procedure, allowing T measurements independent of the heated spot size.

Concluding we can state that the measurement of the lattice temperature of Si during pulsed laser annealing with use of a very direct time-of-flight method supports the thermal theory assuming a molten near surface region.

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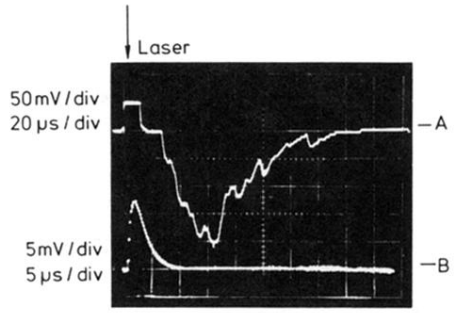

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