

Influence of adsorbates on UV-pulsed laser melting of Si in ultra-high vacuum

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Abstract. The dynamics of laser melting of atomically clean Si is investigated in ultra-high-vacuum (UHV) by transient reflectivity with single-pulse sensitivity in the presence of monitored amounts of chlorine, oxygen or propene. Adsorption of one monolayer (1 ML) leads to measurable variations of the melting dynamics, which are strongly adsorbate-dependent. The variations differ qualitatively and quantitatively from those observed with heavy exposures to gases. The melting dynamics returns to that of clean Si upon subsequent irradiation by laser pulses without readsorption. The required number of pulses for return to clean Si dynamics depends strongly on the type of adsorbate. Adsorbate-induced changes of absorption and reflectivity, and/or incorporation of adsorbates into the substrate, do not explain the results. By contrast, the variations of the melting dynamics are correlated to the photoemitted electron yield, suggesting that laser melting is sensitive to the presence of electrons in the conduction band. These results show that accurate modelling of laser melting of Si interacting with gases should take into account the presence of the gases.

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Laser processing of semiconductors in the presence of gases has been a continuing field of research over the last 20 years. Adsorbates on Si experience strong effects induced by UV-laser melting: desorption from Si, diffusion in liquid Si, and segregation at the solid/liquid frontier during recrystallization. While diffusion in the liquid phase does not vary significantly with adsorbate, desorption and segregation at the Si liquid/solid interface depend strongly on the chemical nature of the adsorbates. After a single pulse, the undesorbed fraction of adsorbates may be located at the surface or in the region of the volume that was melted, influencing strongly the desorbed fraction at the next pulse. This interplay between

desorption and segregation results in very different types of surface modifications: cleaning, etching, doping, dopant profile redistribution. The melting dynamics can be measured through time-resolved measurements of the Si reflectivity at wavelengths where solid and liquid Si have very different reflectivities [1]. Numerical simulations assume the instantaneous conversion of electronic excitation into heat, and calculate the temperature depth and time profiles as a result of laser absorption and heat flow. The result can be compared to transient reflectivity (TR) and time-unresolved measurements, like impurity depth profile [2], time-of-flight mass spectrometry, and Auger electron spectroscopy (AES) [3]. The competition between desorption and diffusion to the bulk was studied in the case of Cl experimentally [4] and numerically [3], showing that the branching ratio between desorption and diffusion to the bulk is “decided” in the first ns of melting. The surface is almost completely depleted from adsorbates during melting.

We observed previously that the melting dynamics of Si depends strongly on chlorine pressure in high-vacuum experiments [3]. The melting threshold varies by 70 mJ/cm² and the melting duration varies by nearly a factor of two. Since the presence of impurities inherent to high vacuum precluded an interpretation of this experiment, it has prompted us to realize TR measurements under a clean UHV environment. It is the aim of this paper to report results concerning the effect of adsorbates on the melting dynamics in UHV. We studied first clean Si in a large range of laser fluence, and for several temperatures, with an experimental setup allowing to record TR in a single pulse [5]. We included in numerical simulations the dependence of reflectivity on the temperature depth profile of the solid, allowing us to simulate accurately the TRs below and above the melting threshold. Surprisingly, we found that the melting dynamics of clean Si is faster than calculated with a standard thermal model [6]. Within the thermal model, the data could be fitted assuming that heat diffusion is reduced in the solid near the surface during the time of photoexcitation. The interpretation is the following: the normal thermal parameters of Si describe ground state Si where the lattice exchanges energy with a (small) density of conduction band electrons that depends on tem-

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perature, through electron–phonon scattering. In the presence of photoexcitation, the conduction band electron density is larger than at thermal equilibrium, with the implication that the lattice is not exactly in the same state (photoexcitation promotes electrons from bonding to antibonding states, which produces lattice distortions). It follows the observed modification of thermal properties. In addition, as the conduction band electron density increases, electron energy relaxation is more and more related to lattice distortions, as is suggested by femtosecond (fs) experiments where melting is faster than electron–phonon scattering [7]. “Non-thermal melting” with fs pulses corresponds to a conduction-band electron density of ca. $5 \times 10^{21} \text{ cm}^{-3}$ [8], while a density of ca. $5 \times 10^{20} \text{ cm}^{-3}$ is estimated in ns laser melting [9]. Since adsorbates modify the electronic structure, a possible test of the role of photoelectrons in laser melting is to study it in the presence of adsorbates: this is the aim of the present work. Chlorine, oxygen and propene are selected for their technological relevance (Cl, O) and/or for their importance as native Si contaminants (O, C). They differ in their chemisorption, desorption and segregation.

1 Experimental

Experiments are carried out under a base pressure of 2×10^{-10} mbar on B-doped 1.5 $\Omega \text{ m}$ Si (100) surfaces. Si cleaning is by heating at 350 °C for 12 h followed by a short anneal to 1100 °C. It is checked by LEED and AES. Sharp LEED patterns are observed before and after laser processing. The intensity of a *s*-polarized, cw probe laser diode at 675 nm is recorded with a time resolution of 2 ns after its reflection on the silicon sample. The reflected beam is passed through an interference filter and detected by a fast semiconductor detector, the linearity of which is carefully checked. Melting is induced by a pump XeCl laser at 308 nm. Fresh excimer gases were always used for the measurements. The angles of incidence are 0° and 12° for the pump and probe lasers, respectively. The pump beam passes through a lens array homogenizer. The plane where the energy distribution is homogeneous is optically conjugated with the sample, the size of the uniformly irradiated area being $\sim 2 \times 3 \text{ mm}^2$. The sample is also optically conjugated with a fast detector, which allows us to record the relative intensity of the reflected beam. The absolute precision on the measurement of the laser fluence is estimated to be 8% (based on imprecisions in the evaluation of beam uniformity, losses on the UHV chamber window, the size of the laser spot, and the power meter). However, pulse-to-pulse variations are much smaller, as will be shown below. The size of the probe laser spot on the sample is 0.1 mm². Charges photoemitted by the excimer pulse are collected at 5 mm from the sample on a filament electrode (1-mm diameter, biased +90 V with respect to the sample to ensure that all photoemitted electrons are collected). The time resolution of ca. 50 ns does not allow the investigation of the time dependence of electron emission. At 308 nm only electrons of the conduction band can be photoemitted by absorption of one single photon. The photoelectron current thus reflects the conduction-band electron density. All signals are recorded on a digital oscilloscope (500-MHz bandwidth) in one single laser shot. Adsorption is made before laser pulses by introducing chlorine, oxygen or propene at a typical pres-

sure of 10^{-8} mbar for a time allowing the completion of 1 ML. In the case of Cl₂, adsorption is made in a separate chamber. The dose is controlled by AES. The cleanliness of gases is controlled with a quadrupole mass spectrometer. The shape of the TR as a function of laser fluence was described in detail in [5]. In this work, the pulse energy is kept in the range of ca. 500–600 mJ/cm², resulting in a maximum reflectivity R_{max} of ca. 0.6 that corresponds to a melted depth of ca. 12 nm. R_{max} increases with melted depth as long as the latter is smaller than ca. 20 nm, the absorption length at 675 nm. Beyond this value, it is equal to the reflectivity of liquid Si (0.7). The melting duration Δt is the TR width, taken at $R = 0.4$, the reflectivity of solid Si at the melting temperature.

2 Numerical simulation of desorption, diffusion, segregation

We first examine numerically what is the concentration depth profile induced by one laser pulse on 1 ML of Cl, O, or propene (Fig. 1). We use a numerical simulation code initially developed to describe laser etching of Si by chlorine [3]. The code calculates the evolution of a foreign atom depth concentration (initially present only at the surface) caused by

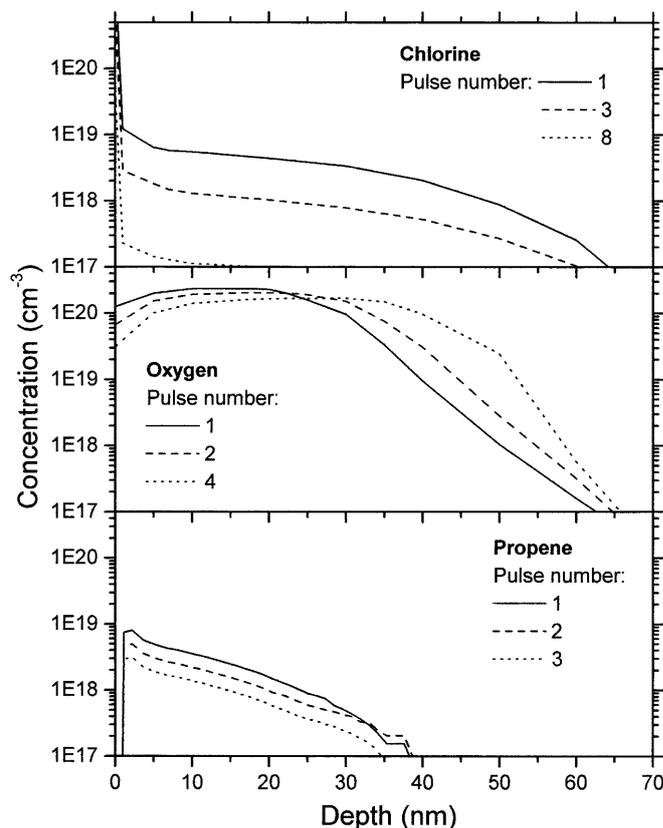


Fig. 1. Calculated concentration depth profiles of Cl, O, and C, following surface melting induced by successive laser pulses of 600 mJ/cm² at 308 nm having the temporal profile shown in Fig. 2b. The number associated with each curve is the pulse number. For the curves labeled “1”, 1 ML of Cl, O, and propene, respectively, is adsorbed and the bulk is initially clean. There is no reabsorption between laser pulses. The parameters used to characterize desorption and segregation are listed in Table 1. The Cl profiles are upper limits corresponding to a segregation coefficient of 0.02

a laser-induced temperature jump and the formation of a liquid layer. Laser heating and melting are first calculated. The resulting surface temperature and melted depth as a function of time are used as inputs in the calculation of the Cl diffusion. In the calculation of heating and melting, standard thermal parameters of Si are used. Since they do not account for the experimental melting dynamics, the laser pulse duration is used as a parameter in order to match the experimental melting duration. In this way, the Cl diffusion calculation is based on accurate melting dynamics. In the atom diffusion program, the Cl concentration depth profile varies under the effects of diffusion in the melted layer, segregation at the liquid/solid interface, and desorption. The parameters describing these processes are the diffusion coefficient of Cl in liquid Si, the segregation coefficient, and thermal desorption kinetic parameters (Table 1). The segregation and desorption parameters were obtained for Cl by comparing experimental and calculated concentration profiles, Cl Auger signals, and etching rates, at the end of a laser pulse, which together provide a strong constraint on the determination of the desorption and segregation parameters. Details of the calculation are given in [3]. The code has been used for O and propene, using the appropriate parameters (Table 1). A difference of 0.5 eV is applied between the desorption energies from liquid and solid Si, corresponding to the Si latent heat of melting; this was found to fit the desorption kinetics in the case of Cl [3].

Chlorine chemisorbs dissociatively on Si [10]. It does not diffuse inside Si at room temperature [11]. It experiences a strong segregation at the liquid/solid Si interface [3]. The ca. 40% fraction of undesorbed Cl spends the time of the laser pulse inside the melted layer, but is found mostly at the surface after the pulse, due to segregation [3, 4]: Cl is a case where the final bulk contamination is small, if not negligible. Oxygen adsorbs dissociatively, although there are also long-lived molecular precursors [12]. Its desorption energy is similar to that of Cl [13]. It diffuses spontaneously inside Si even at ambient temperature (although on a quasi-infinite time scale with respect to the duration of the present experiments), and it experiences a retrograde segregation at the liquid/solid interface of Si [14]: O stays inside Si after melting. Cl and O have similar desorption energies, but the O concentration at the surface is small after a laser pulse:

Table 1. Parameters describing desorption from solid and liquid Si, and segregation at the Si liquid/solid interface, used in the calculations shown in Fig. 1. The pre-exponential factor for desorption, and the diffusion coefficient, are taken to be 10^{14} s^{-1} and $1.6 \times 10^{-4} \text{ cm}^2 \text{ s}^{-1}$ for all three adsorbates

	Desorption energy (solid) (eV)	Desorption energy (liquid) (eV)	Segregation coefficient
Chlorine	3.7 ^a	3.2 ^a	< 0.02 ^{a,b}
Oxygen	3.8 ^c	3.3 ^d	1.25 ^e
Propene	1.7 ^d	1.2 ^d	0.07 ^e

^a See [3].

^b 0.02 is an upper limit corresponding to the detection sensitivity of Cl in [3].

^c See [11].

^d See text.

^e See [12].

this is why it takes 1000 laser pulses to clean Si from native O down to undetectable levels, while a few laser pulses are sufficient to desorb 1 ML of Cl [4]. Propene chemisorbs on Si without dissociation [15]. However, at the high temperature achieved in the present experiments, CH and CC bonds are broken and all H atoms desorb: only peaks related to Si–C vibrations are observed in Fourier-Transform IR (FTIR) absorption experiments performed on samples after a large number of laser pulses with resaturation of the surface by propene between pulses [16, 17]. The unknown desorption energy of propene is assumed to be equal to that of ethylene [18], significantly smaller than in the case of Cl and O. C experiences a moderate segregation at the liquid/solid interface of Si [14]. Ninety-eight percent of the propene ML is calculated to desorb, 90% being already desorbed when the surface starts melting: propene is a case where bulk contamination is limited by desorption: the surface is calculated to be enriched (with respect to volume) in Cl and depleted in C (Fig. 1).

3 Experimental results

3.1 Chlorine (Fig. 2a)

Single-shot TR records of a chlorinated Si surface are shown in Fig. 2a in comparison with the TR of the clean substrate. At the first shot, melting is deeper and lasts longer than on clean Si, as shown by a 9% increase of R_{max} and a ca. 20% increase of Δt . If Cl is not readsorbed, R_{max} returns to the value of the clean substrate after three laser shots, but it takes ca. eight shots for Δt to return to its initial value. Thus Δt is more sensitive than R_{max} to the presence of Cl. Since Cl is also undetectable by Auger measurements after ca. three pulses [4], Δt is sensitive to a few 10^{-3} ML of Cl. After a ca. 20% enhancement of the electron emission at the first shot and the presence of desorbed ions (SiCl^- and SiCl_2^-) in the slow tail of the signal, return to the clean Si electron emission is observed after ca. four laser shots. The insert of Fig. 2a shows the laser-intensity temporal profile for the same three laser pulses as in the main figure, showing that the intensity fluctuations of the laser are negligible. Comparison with [3] shows that incorporation of Cl in a high vacuum and in UHV have opposite effects. This is most probably related to the presence of other foreign atoms that behave differently from Cl in the high-pressure environment, and it justifies the present work in UHV.

3.2 Oxygen (Fig. 2b)

At the first shot, the effect of O adsorption is opposite to that of Cl, with a reduction of ca. 6% of R_{max} and of ca. 8% of Δt , and a much smaller electron emission. Return to the clean Si TR (not shown in the figure) takes many more laser pulses than for Cl (ca. 1000 instead of eight): this is readily explained by the much larger desorption yield of Cl. On the figure is also shown the TR at the second pulse after readsorption of oxygen: R_{max} and Δt have decreased by another ca. 6% and ca. 8%, respectively. In addition, the reflectivity just before melting is larger at pulse 2 than at pulse 1. There are no more variations of the TR between pulses 2 and 6. This is

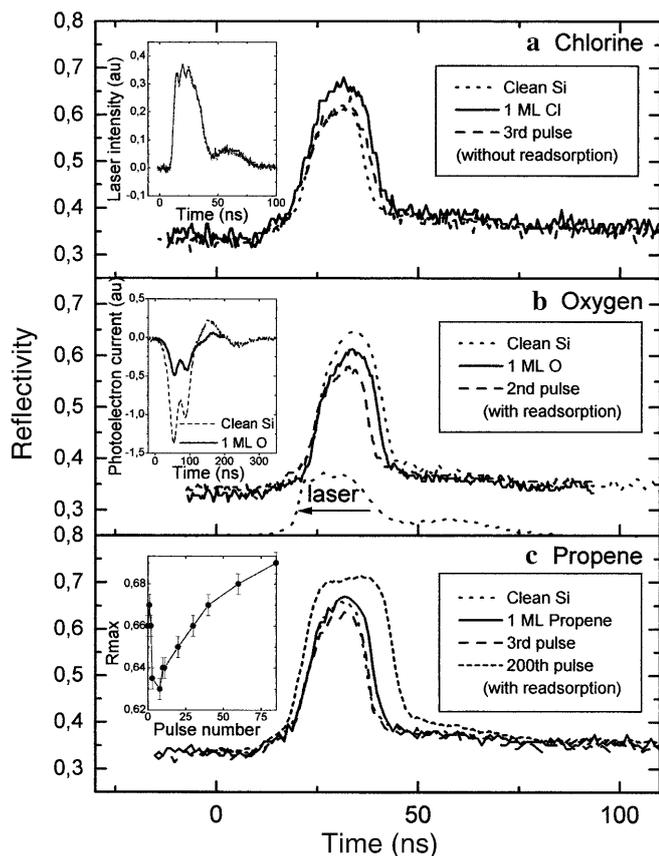


Fig. 2a–c. Experimental single-pulse transient reflectivity (TR) records of Si at 675 nm in the presence of **a** chlorine, **b** oxygen, and **c** propene. The TR is induced by a laser pulse of ca. 600 mJ/cm^2 at 308 nm. The actual laser energy varies slightly with the adsorbate. A typical temporal profile is shown in **b**. In each case, the TR of clean Si is also shown, together with the TR of a subsequent laser pulse, with or without readsorption, as indicated. The *inset* in **a** displays the three records of the laser intensity, as measured with a fast photodiode, corresponding to the three TRs of the main figure, showing the very small pulse-to-pulse variations of the laser intensity. The *inset* in **b** displays the laser-induced electron current for clean and O-covered Si. The *inset* in **c** shows the variation of the maximum reflectivity as a function of laser count when propene is readsorbed before each laser pulse

intriguing, since the O concentration in the volume probably increases roughly linearly with the pulse number. However, anticipating the discussion, if we take the electron emission yield as an indicator of the effect of O on the melting dynamics, its very large decrease ($\sim 2/3$) at the first pulse (insert of Fig. 2b) suggests that the effect should saturate quickly with laser pulse number.

3.3 Propene (Fig. 2c)

1 ML of propene has an effect similar to Cl, although not as strong. R_{max} and Δt increase by ca. 1.5% and ca. 7%, respectively. Since the effect of propene is probably limited by the small fraction of C that remains in or on Si, the experiment was repeated with readsorption of propene over a large number of laser pulses. After the slight increase observed at pulse 1, R_{max} and Δt decrease between pulses 2 and 8, and then increase up to values much larger than on clean Si until ca. pulse 200 (insert of Fig. 2c). At this pulse number, R_{max} and Δt have increased by ca. 10% and 50% with respect to clean

Si. After pulse 200, the static reflectivity also starts to change measurably, in relation to the formation of a SiC layer as shown by FTIR measurements to be reported elsewhere [16]. This is consistent with incorporation of ca. 0.02 ML per pulse that remain close to the surface, as calculated in Sect. 1. Electron emission varies during the first laser shots like in the case of Cl, with an increase of ca. 8% at the first pulse and the occurrence of a tail at long times which corresponds to the desorption of anions.

4 Discussion

In the case of readsorption, differences between the first and second pulses reflect the influence of the adsorbates that have been brought into the bulk at the first pulse. Their amount is small for Cl and is expected to vary little with pulse number. It is larger for O. The influence of bulk O is quantitatively similar to that of surface O. In the case of propene, the first laser pulse interacts with Si–propene only, but the second interacts with Si–propene and Si–C. These seem to have opposite effects. Si–propene is similar to Si–Cl. Si–C at ca. 10^{-2} ML concentration is similar to Si–O. SiC at ca. 1 ML concentration (i.e. after ca. 200 pulses) affects the TR much more strongly, and with opposite trends as a function of pulse number, suggesting that the mechanism responsible for the TR variation with pulse number is different for “small” (10^{-2} ML) and “large” (1 ML) amounts of C.

We now consider plausible explanations for the observations. TR variations may be ascribed to several factors that can be affected by the presence of adsorbates: (a) the visible reflectivity: adsorbates induce reflectivity changes up to a few percent in the visible and near-UV. On Si, these changes are related to dangling bond saturation [19]. We observe a measurable change of the static reflectivity at 675 nm only in the case of propene after 200 laser pulses with propene readsorption at each pulse. The transient reflectivity has no reason to vary more than the static one, and such small variations of the reflectivity can hardly explain changes of the TR width. (b) The UV reflectivity modifies the fraction of laser energy absorbed by Si, possibly resulting in variations of the TR width. Adsorbate-induced variations of the UV reflectivity at 308 nm are expected to be of similar importance as in the visible. The change of R at 308 nm is known in the case of O_2 (+0.6%) [20]. This is equivalent to a 0.9% decrease of the laser energy (taking into account the reflectivity of 0.6 at 308 nm). However, at 600 mJ/cm^2 more than 80% of the laser energy arrives on the sample when it is already liquid (Fig. 2b). Variations of the liquid reflectivity are expected to be much smaller than on the solid, because a fraction of adsorbates has desorbed, and the rest is distributed over a depth that extends more into the bulk than the UV optical depth. The 0.9% decrease of the solid reflectivity would then result in a decrease of the laser energy of ca. 0.2%. This corresponds to a decrease of the melting duration of ca. 0.4% based on our calculations of [3], smaller than observed by a factor of 18. (c) The UV absorption determines the location of laser energy deposition, but its influence can be ruled out in the present case because the absorption length (6 nm) is much smaller than the heat diffusion length corresponding to the pulse duration (1 μm): heat diffusion controls the melting dynamics, not absorption. (d) The thermal properties can be modified

through chemical modification of Si. The amount of incorporated atoms can be evaluated using the data of Fig. 1. The peak of O concentration below the surface after the first pulse is ca. $2 \times 10^{20} \text{ cm}^{-3}$ (or a molar fraction of 4×10^{-3} with respect to Si). The peak concentration of C is ca. $8 \times 10^{18} \text{ cm}^{-3}$ (or a molar fraction of ca. 3×10^{-4}). The molar fraction with respect to the melted layer is even smaller (ca. 2×10^{-3} and ca. 3×10^{-5} for O and C, respectively). For such small amounts of impurities, the variation of the heat capacity and thermal conductivity should follow a monotonic variation with pulse number, and be much larger in the case of O ("fast" evolution towards SiO) than in the case of C ("slow" evolution towards SiC): this is not observed. As pointed out above, the TR does not vary after pulse 2 in the case of O, while C has an influence of a similar strength as O. In addition, chemical modification, where it definitively cannot be ignored (pulse numbers between 9 and 200 for C), leads to a variation with a pulse number which is opposite to the variation at small pulse numbers. Therefore, the observed effect of adsorbates at the first laser shots cannot be due to a chemical effect.

To summarize, adsorption of 1 ML of chlorine, oxygen or propene leads to measurable and reversible variations of the melting dynamics. These variations are strongly adsorbate-dependent and even pulse number-dependent, and cannot be explained by adsorbate-induced changes of absorption and reflectivity, or by the formation of a layer chemically different from the substrate (the case of propene illustrates the opposite effects of sub-ML and ML concentrations). Having eliminated these explanations, we are led to consider the role of excited electrons and the interplay between excited electrons and adsorbates. The electron emission yield is expected to reflect the conduction band electron density. We observe that electron emission by the laser pulse is correlated to the TR width: the larger the width, the larger the electron emission yield. This supports the idea previously proposed in our study of clean Si that a high density of photoelectrons enhances surface melting. The proposed mechanism for clean Si is Si–Si bond weakening and lattice distortion. Foreign atoms may interfere in two ways. The first way is band bending: the formation of the doubly charged layer at the surface drives electrons to, or away from, the surface. This effect should increase with adsorbate electronegativity. The second way is that foreign atoms induce defects during heating where charges may be captured. The observations suggest that Cl and O are not active through the same mechanism. Cl would be active through band bending, while O would be active through SiO defects that would capture electrons. Similarly, adsorbed propene would act through band bending while SiC defects would act like SiO defects. A full SiC layer would act through overall different thermal and optical properties.

5 Conclusion

Laser melting with a nanosecond laser is sensitive to the presence of adsorbates at a dose of 1 ML. Although melting is

a thermal process in the sense that it is controlled by photon absorption and heat flow, photoexcited electrons were suggested to play a quantitative role in the melting dynamics by modifying the thermal conductivity and heat capacity [5]. The adsorbate-induced variations of optical properties are too small to account for the observations. Therefore variations of heat capacity and thermal conductivity with adsorbates must explain them. The experimental results rule out the effect of material change by dilution of adsorbates into Si: in particular, adsorbates appear too diluted in the melted layer by comparison with heavier doses of adsorbates which produce different effects on the melting dynamics. Therefore, we attribute the effect of 1 ML of adsorbates on the melting dynamics to the coupling between adsorbates and photoelectrons.

The present results show that modeling of laser melting, although very useful, must be handled with care, especially when comparing experimental results under different environments. Even dopants may be suspected to influence the melting dynamics. In low-vacuum experiments, melting allows the simultaneous incorporation of desired and undesired impurities, with unpredictable results for the melting dynamics.

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References

1. G.E. Jellison, Jr., D.H. Lowndes, D.N. Mashburn, R.F. Wood: *Phys. Rev. B* **34**, 2407 (1986)
2. R.F. Wood, G.E. Giles: *Phys. Rev. B* **23**, 2923 (1981); R.F. Wood, J.R. Kirkpatrick, G.E. Giles: *Phys. Rev. B* **23**, 5555 (1981); R.F. Wood: *Phys. Rev. B* **25**, 2786 (1982)
3. B. Dragnea, J. Boulmer, J.-P. Budin, D. Débarre, B. Bourguignon: *Phys. Rev. B* **55**, 13904 (1997)
4. B. Bourguignon, M. Stoica, B. Dragnea, S. Carrez, J. Boulmer, J.-P. Budin, D. Débarre, A. Aliouchouche: *Surf. Sci.* **338**, 94 (1995)
5. B. Dragnea, B. Bourguignon: *Phys. Rev. Lett.* **82**, 3085 (1999)
6. S. De Unamuno, E. Fogarassy: *Appl. Surf. Sci.* **36**, 1 (1989)
7. P. Saeta, J.K. Wang, Y. Siegal, N. Bloembergen, E. Mazur: *Phys. Rev. Lett.* **67**, 1023 (1991)
8. P.L. Silvestrelli, A. Alavi, M. Parrinello, D. Frenkel: *Phys. Rev. Lett.* **77**, 3149 (1996)
9. H.M. van Driel: In *Interfaces under Laser Irradiation*, NATO ASI series E 134 (1987) p. 105
10. G.A. de Wijs, A. De Vita, A. Selloni: *Phys. Rev. B* **57**, 10021 (1998)
11. M. Seel, P.S. Bagus: *Phys. Rev. B* **28**, 2023 (1983)
12. T. Rhodin, *Prog. Surf. Sci.* **50**, 131 (1995)
13. T. Engel: *Surf. Sci. Rep.* **18**, 91 (1993)
14. S. Wolf, R.N. Tauber, *Silicon Processing for the VLSI Era*, Vol. 1 (Lattice Press, Sunset Beach, 1992) p. 251
15. M.J. Bozack, P.A. Taylor, W.J. Choyke, J.T. Yates, Jr.: *Surf. Sci.* **177**, L933 (1986)
16. B. Dragnea, J. Boulmer, D. Débarre, B. Bourguignon: *J. Appl. Phys.* **90**, 449 (2001); B. Dragnea, Ph.D. Thesis (University of Paris-Sud 1997)
17. J. Boulmer, C. Guedj, D. Débarre: *Thin Solid Films* **294**, 137 (1997)
18. L. Clemen, R.M. Wallace, P.A. Taylor, M.J. Dresser, W.J. Choyke, W.H. Weinberg, J.T. Yates, Jr.: *Surf. Sci.* **268**, 205 (1992)
19. C. Noguez, C. Beitia, W. Preyssa, A.I. Shkrebtii, M. Roy, Y. Borenstein, R. Del Sole: *Phys. Rev. Lett.* **76**, 4192 (1996)
20. E.G. Keim, L. Wolterbeek, A. van Silfhout: *Surf. Sci.* **180**, 565 (1987)