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1 **Kinetics and coupled dynamics of dewetting and chemical reaction**  
2 **in Si/SiO<sub>2</sub>/Si system**

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Abstract

We report on the observation of a coupling between the dewetting of a Si layer on SiO<sub>2</sub> induced by surface/interface energy minimization and the etching between both materials due to the Si+SiO<sub>2</sub>  $\rightarrow$  2 SiO<sub>g</sub><sup>↑</sup> reaction. In the limit of a thin SiO<sub>2</sub> layer ( $\leq$  10 nm) sandwiched between a Si layer and a Si handle wafer, the front of Si dewetting and the front of SiO<sub>2</sub> etching coexist in a narrow region. The interplay between both phenomena gives rise to specific morphologies. We show that extended Si fingers formed by dewetting are stabilized with respect to Rayleigh Plateau type instability over tenth of microns thanks to a localized etching of the SiO<sub>2</sub> layer. The break up of this structure occurs abruptly by an unzipping process combining dewetting and etching phenomena. We also put in evidence that Si rings are created with a thin SiO<sub>2</sub> layer in the center. These processes are thermally activated with an activation energy of  $2.4 \pm 0.5$  eV and  $4.0 \pm 0.5$  eV respectively for dewetting and the etching reaction. All these results highlight the respective roles of wetting and etching in Si/SiO<sub>2</sub>/Si system dynamics and could be a stepping stone for the development of advanced processes based on Silicon-On-Insulator technology.

## 7 I. INTRODUCTION

8 Wetting of liquids on solids in reactive systems is of great importance with many industrial  
9 applications such as soldering or adhesion [1]. The kinetics of reactive wetting is affected  
10 by a number of factors like interfacial reactions, diffusion of constituents or dissolution of  
11 the substrate [2 and 3]. Under reaction the contact line dynamics can lead to complex  
12 behaviours such as oscillatory phenomenon of spreading and contraction [4–7], formation  
13 of reaction rings [8] or even droplet motion [9–11]. For example, the reaction-mediated  
14 spontaneous drift of millimeter-scale solid-state camphor particles on the surface of water  
15 has been known for several centuries [12]. In solid systems only scarce studies have explored  
16 the coupling between chemical reactions and wetting dynamics. For instance in metallic  
17 systems the alloying driving force can induce the self-propelled motion of solid Sn islands  
18 onto a Cu surface [13]. In the context of metal/oxide or semiconductor/oxide systems, solid  
19 state wetting properties may also be affected by interfacial redox reactions. For instance in  
20 the Si/SiO<sub>2</sub> couple, that plays a key role in the perspective of future devices based on Silicon-  
21 On-Insulator (SOI) technology [14–17], wetting and reactivity properties of the interface have  
22 been largely studied. Under moderate annealing ( $\sim 1100$ - $1300$  K) SOI dewetting occurs  
23 by edge retraction (see Fig.1 and [18–24]), the expelled silicon accumulates in a receding  
24 rim that exhibits a capillary instability giving birth to elongated Si structures (called Si  
25 fingers). These fingers are in turn destabilized and periodically form 3D Si islands by  
26 a beading mechanism similar to a Rayleigh-Plateau instability. The driving force for this  
27 dewetting process arises from the surface/interface free energy gain. In solids mass transport  
28 is mediated by surface diffusion [25–27] whereas hydrodynamics dominates in liquid films  
29 [28–31]. This makes that the contact line with the substrate is particularly sensitive to the  
30 effect of the disjoining pressure in solid thin films whereas surface diffusion is much less  
31 affected [32]. Considering high temperature regimes ( $\sim 1300$  K) Si and SiO<sub>2</sub> solids are also  
32 known to react and form volatile SiO<sub>g</sub><sup>†</sup> molecules. This is perfectly illustrated when a SOI  
33 film is completely dewetted at 1000 K, then annealed at 1330 K: the reaction leads jointly  
34 to the consumption of the 3D Si islands and to the etching of nanopits in the SiO<sub>2</sub> layer [33  
35 and 34].

36 In this article we analyze the combined effects of etching reaction and dewetting on SOI  
37 films in the high temperature regime. Their interplay gives complex front dynamics: (i)

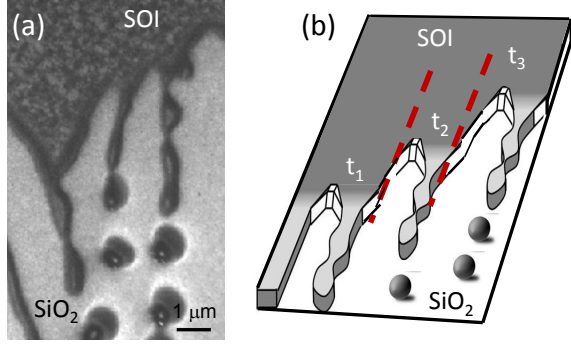


FIG. 1. (a) Low energy electron microscopy image of the dewetting of a SOI film ( $\sim 20$  nm thick) at 1160 K. (b) sketch of the dewetting mechanism: a Si finger destabilizes by a lateral undulation (time  $t_1$ ) that leads to beading and formation of a 3D Si island at its extremity (time  $t_2 \sim t_1 + 120$  s). This process repeats periodically (time  $t_3 \sim t_1 + 240$  s).

38 formation of extended Si fingers stabilized by lateral etching, (ii) Si fingers break up by an  
 39 unzipping mechanism and (iii) formation of Si rings with a thin  $\text{SiO}_2$  layer in the center.  
 40 The etching and dewetting fronts dynamics are studied experimentally *in situ* and in real  
 41 time by low energy electron microscopy (LEEM) and *ex situ* AFM measurements.

## 42 II. METHODS

43 The SOI wafers are originally fabricated at SOITEC (Bernin, France). They are cleaned  
 44 and prepared in Ultra High Vacuum (UHV) conditions as described in Ref. [35]. The studied  
 45 thickness is about 30 nm for the Si layer and 8 nm for the buried oxide layer (BOX) of  $\text{SiO}_2$ .  
 46 Such thin structures are highly sensitive to Si layer dewetting and etching reaction between  
 47 Si/ $\text{SiO}_2$  under thermal annealing. In the temperature range  $\sim 1300 - 1400$  K, a front of  
 48 dewetting of the Si layer forms spontaneously onto a defect at the surface/interface and is  
 49 followed by an etching reaction front. Their motion and morphology are recorded *in situ* and  
 50 in real time (1 s per image) by low energy electron microscopy (LEEM) in the tilted bright  
 51 field mode (electron energy: 4 eV). The characterization of the coupling between the etching  
 52 and dewetting fronts dynamics is completed by *ex situ* analysis of the surface morphology  
 53 by atomic force microscopy (AFM, PSIA-XE 100).

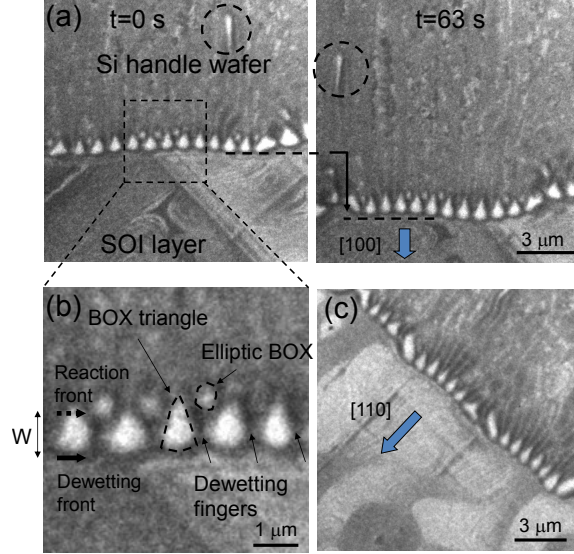


FIG. 2. (a) Sequence of two LEEM images of a thin SOI layer (30 nm) onto a BOX layer (8 nm) at 1370 K. The SOI dewetting front and the etching front Si/SiO<sub>2</sub> advance in the [100] direction (See Supplemental Material S1 at [URL will be inserted by publisher] for the complete movie). The Si handle wafer is on top of the image and the SOI layer is at the bottom. Dotted circles: SiO<sub>2</sub> layers moving opposite to the dewetting/etching front. The linear defects in the SOI layer (bottom right part of the image) occur due to remaining lateral temperature gradients during annealing. They have no influence on the fronts dynamics. (b) Close view of the area of coexistence of the dewetting front (black arrow) and reaction front (dashed arrow): The exposed SiO<sub>2</sub> layer has a bright contrast with a triangular or elliptical shape. Si fingers are formed in between triangular SiO<sub>2</sub> layers. (c) Same as (a) for an advancing front in the  $\langle 110 \rangle$  direction.

### 54 III. RESULTS: INTERPLAY BETWEEN ETCHING REACTION AND DEWET- 55 TING FRONTS

#### 56 A. Kinetics of fronts propagation

57 Figure 2(a) shows two LEEM images of the SOI (30 nm)/BOX (8 nm)/Si handle wafer  
58 during solid phase etching and dewetting at 1370 K. The SOI layer exhibits a black/white  
59 contrast coming from the  $(1 \times 2)/(2 \times 1)$  surface reconstructions. The SOI dewetting front ap-  
60 pears as an undulating grey line (fig. 2(b)) that separates the SOI layer and the underneath  
61 SiO<sub>2</sub> BOX layer (bright contrast). The fronts recede in a steady state at a constant velocity

62 of  $53 \pm 5 \text{ nm.s}^{-1}$ . If the front is aligned along the  $[100]$  direction very regular structures  
 63 ( $1.5 \pm 0.1 \text{ }\mu\text{m}$  period) occur whereas slightly more disordered ones can be observed when the  
 64 front recedes in the  $[110]$  direction (Fig. 2(c)). A similar observation is obtained for Si(001)  
 65 thin layer dewetting onto  $\text{SiO}_2$  at lower temperature (1200 K) when etching reaction is neg-  
 66 ligible. The  $[100]$  front forms regular fingers by front edge instability as described by [36].  
 67 In the case of a  $[110]$  front, as there are two equivalent directions for the fingering instability  
 68 ( $[100]$  and  $[010]$ ), the competition between both degrades the long range order [23 and 24].

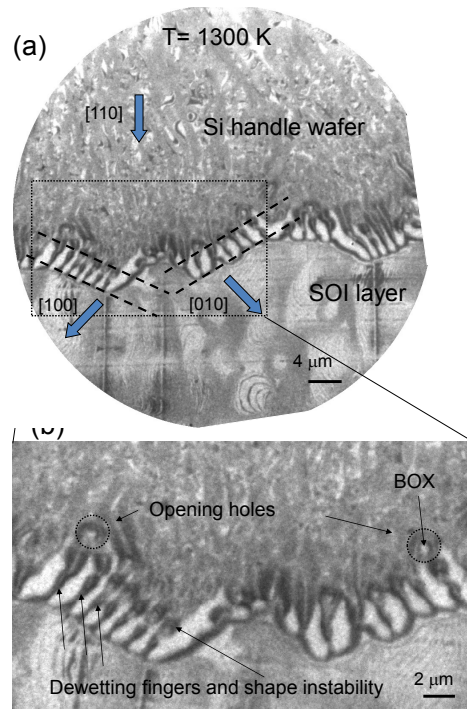


FIG. 3. (a) LEEM image of a SOI layer (30 nm) onto a BOX layer (8 nm) at 1300 K (See Supplemental Material S2 at [URL will be inserted by publisher] for the complete movie). The SOI dewetting front and the etching front Si/SiO<sub>2</sub> (middle) advance in the  $[110]$ . (b) Close view of the fronts: Si fingers onto SiO<sub>2</sub> layer are visible (black arrows) as well as circular holes in the Si layer (black dotted circles) exposing SiO<sub>2</sub>.

69 As the SOI dewetting fronts recede (*via* fingers formation), the underlying SiO<sub>2</sub> BOX  
 70 layer is exposed to vacuum (Fig. 2(b)). This free BOX layer shows triangular structures,  
 71 the base pointing towards the SOI layer and the tip pointing in the direction of the Si handle  
 72 wafer. We can infer that the edges of the triangles correspond to the reaction front between  
 73 the remaining BOX layer and the Si handle wafer. As the front recedes in a steady state, the

74 decay of the BOX occurs by a constant etching reaction rate ( $\text{Si} + \text{SiO}_2 \longrightarrow 2 \text{SiO}_g^\uparrow$ ) localized  
75 at the Si/SiO<sub>2</sub>/vacuum triple-line. To evaluate the activation energies of SOI dewetting  
76  $E_d$  and etching reaction  $E_r$  we have studied the effect of the sample temperature on both  
77 kinetics (Fig. 3(a)-(b)). As the temperature decreases from 1370 K to 1300 K the fronts  
78 velocity  $v_f$  decreases from  $53 \pm 5 \text{ nm.s}^{-1}$  to  $18 \pm 3 \text{ nm.s}^{-1}$ , the extension of the free BOX  
79 layer  $W$  increases from  $0.9 \pm 0.1 \text{ }\mu\text{m}$  to  $2.3 \pm 0.5 \text{ }\mu\text{m}$  and the disappearance time  $t_d$  of the free  
80 BOX layer increases from  $20 \pm 1 \text{ s}$  to  $125 \pm 20 \text{ s}$ . The SOI front velocity  $v_f$  is only driven by  
81 SOI dewetting kinetics and can be written as  $v_f \sim e^{-\frac{E_d}{kT}}$  assuming it is thermally activated.  
82 From the ratio of the velocities  $v_f$  at 1370 K and 1300 K, the dewetting activation energy  
83 is estimated as  $E_d = 2.4 \pm 0.5 \text{ eV}$  that is in perfect adequation with previous SOI dewetting  
84 studies [23] that show that Si surface diffusion is the dominant mechanism of mass transport  
85 mediating the dewetting process. The etching reaction activation energy  $E_r$  is not related  
86 to the reaction front velocity. Indeed the reaction occurs at the Si/SiO<sub>2</sub>/vacuum triple-  
87 line and thus starts when the BOX is exposed to vacuum. Therefore the etching reaction  
88 activation energy has to be evaluated from the disappearance time  $t_d \sim e^{\frac{E_r}{kT}}$  of the free BOX  
89 layer. Measurements of  $t_d$  at 1370 K and 1300 K provide an estimate of  $E_r = 4.0 \pm 0.5$   
90 eV. This is also in adequation with the activation energy reported by [33] from temperature  
91 dependent measurements of Si island decay kinetics onto SiO<sub>2</sub>. At last we have also measured  
92 the width  $W$  of the exposed BOX layer with respect temperature. It is related both to  
93 dewetting and etching reaction activation energies as  $W = v_f \times t_d \sim e^{\frac{E_r - E_d}{kT}}$ . We measure  
94 that  $E_r - E_d = 2.1 \pm 0.6 \text{ eV}$ . The large difference between the activation energies of Si  
95 dewetting and etching reaction makes that the width  $W$  of the free BOX layer decreases  
96 strongly with temperature as observed experimentally. At last let us note that despite the  
97 difference between both activation energies, the dewetting and etching fronts move at the  
98 same velocity (*i.e.* at the Si layer dewetting velocity, see supplementary material S1). This  
99 is due to the fact that the etching reaction occurs only when the BOX layer is exposed to  
100 vacuum, *i.e.* after the dewetting front passage. Then it takes a time  $t_d$  for the BOX layer  
101 to be completely etched which can be seen as a delay time for the etching front to progress  
102 behind the dewetting front.

103 This evaluation of the activation energies can also be completed with the quantitative  
104 analysis of the rate of etching reaction and dewetting front velocity. From the linear decrease  
105 of the BOX layer with time (triangular shape) the reaction rate  $\nu_{\text{reac}} = \frac{dN}{dt}$  at the Si/SiO<sub>2</sub>

106 contact line can be estimated (where  $N$  is the number of  $\text{SiO}_2$  entities in the oxide layer).  
 107 We calculate therefore  $\nu_{\text{reac}} \approx 3.2 \times 10^3 \text{ s}^{-1}$  per  $\text{SiO}_2$  entity at the contact line at 1370 K  
 108 and  $\nu_{\text{reac}} \approx 5 \times 10^2 \text{ s}^{-1}$  per  $\text{SiO}_2$  entity at 1300 K (oxide layer thickness: 8 nm). This  
 109 result compares to previous report [33] on the reaction rate of Si islands onto  $\text{SiO}_2$  ( $3 \times 10^2$   
 110  $\text{s}^{-1}$  per atom) in a slightly lower temperature regime. Concerning the dewetting velocity  
 111 of SOI, Cheynis et al. [24] have shown that in the temperature range [1000 K - 1200 K]  
 112  $v_f \simeq \frac{5.3 \times 10^{12}}{h^3 kT} e^{-2.0/kT} \text{ nm.s}^{-1}$  where  $h$  is the SOI film height expressed in nm and  $kT$  is given  
 113 in eV. Assuming this expression for a 30 nm thick film at 1370 K and 1300 K we obtain  
 114 respectively  $v_f=74 \text{ nm.s}^{-1}$  and  $v_f=31 \text{ nm.s}^{-1}$  which gives the correct order of magnitude of  
 115 the kinetics, the overestimation arising probably from a slightly too low activation energy  
 116 in the modeling.

117 Beyond the description of the energetics of  $\text{SiO}_2$  etching, figures 2(b) and 3(b) show  
 118 also very specific structures that highlight a complex interplay between the dynamics of  
 119 dewetting and etching. This interplay occurs because the timescale for the formation of  
 120 fingers and 3D islands by dewetting is comparable to the timescale for the consumption of  
 121 the BOX layer. We will focus on three main structures: (i)  $\text{SiO}_2$  BOX layer of elliptic shape  
 122 located in between two free BOX triangles and separated by Si (dotted ellipse in fig. 2(b),  
 123 at 1370 K). (ii) Elongated free BOX structures crossing the surface from time to time in the  
 124 direction opposite to the dewetting front (dotted circles in fig. 2(a)) with a large velocity  
 125 ( $> 100 \text{ nm.s}^{-1}$ ). (iii) SOI islands with a ring shape and exposing a circular BOX layer in  
 126 the middle (see fig. 3(b) at 1300 K). To understand all these structures we will describe in  
 127 the following part the main stages of their formation and propose different scenarios with  
 128 coupled etching and dewetting phenomena.

## 129 B. Coupled dynamics of dewetting and etching

130 *a. Steady state elliptic shape BOX structure* Figures 2(a)-(b) show LEEM im-  
 131 ages of a dewetting/reaction front moving along the [100] direction. The regularly spaced  
 132 triangular BOX structures separate Si fingers that are short and perpendicular to the dewet-  
 133 ting front. Some Si fingers are prolonged by BOX elliptic structures (dotted ellipse in fig.  
 134 2(b)) that are stable during the steady motion of the fronts (See complete movie S1 at [URL  
 135 will be inserted by publisher]).



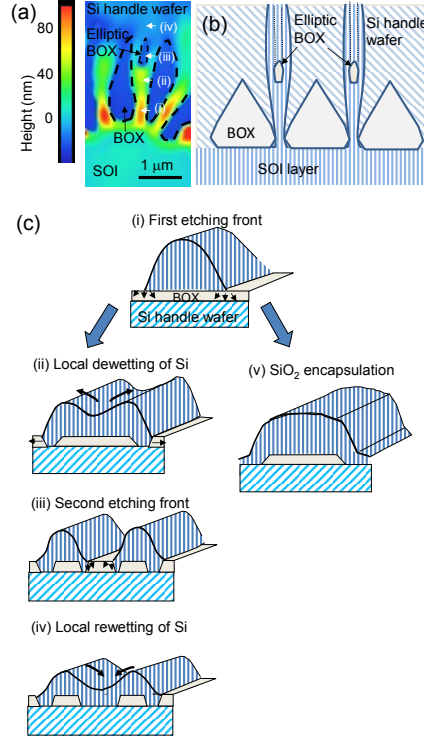


FIG. 4. (a) AFM image of the surface morphology of the front. Si fingers from the SOI layer separated by triangular shape BOX layers are visible. (i) to (iv) address the different steps of Si finger evolution (see scenario in (c)). (b) Scheme of the surface morphology considering elliptic holes (top view). (c) Scenario in four steps of the Si finger evolution: (i) Si finger formed by SOI layer dewetting and simultaneous SiO<sub>2</sub> BOX etching at the contact line. (ii) Complete lateral etching of the SiO<sub>2</sub> layer and contact between the Si finger (from SOI) and the Si handle wafer. Simultaneous lateral progression of the reaction front and Si mass shedding from the center of the finger. (iii) Splitting of the finger into two fingers and occurrence of new etching fronts with the free BOX. (iv) Complete etching of the inner SiO<sub>2</sub> BOX layer and rewetting of the SOI layer onto the Si handle wafer. (i)-(iv) are also sketched on AFM image in (a). (v) Scenario of direct BOX layer encapsulation (without finger splitting).

136 To analyze the morphology of these fronts combining dewetting and etching, figure 4(a)  
 137 shows a typical AFM image. We can clearly distinguish the SOI layer (turquoise) and the Si  
 138 fingers (yellow and red). The AFM image shows also the SiO<sub>2</sub> BOX layer (blue); it appears  
 139 as extremely flat areas located in between Si fingers close to the SOI dewetting front. They  
 140 have the same shape as those observed by LEEM (triangular structures in 2(c)). We can

141 also see from AFM that some Si fingers are unstable and split laterally into two branches  
 142 exposing a small SiO<sub>2</sub> BOX layer (~500 nm) in between (elliptic shape) as the one measured  
 143 by LEEM. From the combination of both methods, a scenario of the process is proposed  
 144 (fig. 4(b)-(c)) based on the combined effects of SiO<sub>2</sub> BOX etching and wetting/dewetting of  
 145 the SOI layer. The scenario involves four steps labelled (i) to (iv) that can be observed also  
 146 by AFM (fig. 4(a)) as time lag is related to the spatial position with respect to the front.  
 147 (i) First, a Si finger is formed by SOI dewetting on the SiO<sub>2</sub> BOX layer. This process is well  
 148 known and arises from surface/interface energy minimization that kinetically destabilizes  
 149 the receding front [37 and 38]. (ii) The Si finger formation results in the occurrence of a  
 150 triple line between the freshly exposed SiO<sub>2</sub> BOX layer, the Si finger and vacuum. This  
 151 contact line is very active for SiO<sub>2</sub> etching compared to SiO<sub>2</sub> dissolution through the SOI  
 152 layer. Indeed, as shown by [39], the limiting mechanism for SiO<sub>2</sub> etching is the diffusion  
 153 of dissolved O atoms created at the Si/SiO<sub>2</sub> interface. When O atoms reach the Si surface  
 154 they combine to Si atoms and create volatile SiO<sub>g</sub><sup>↑</sup> molecules. The diffusion time is therefore  
 155 minimized when O atoms are directly formed at the triple line [33, 34, and 39]. The local  
 156 etching thins locally the SiO<sub>2</sub> BOX layer (~8 nm) until the Si fingers meet the Si handle  
 157 wafer. (iii) This has two consequences: (1) thermodynamically the Si finger tends to spread  
 158 laterally on the Si handle wafer thanks to perfect wetting. (2) Kinetically the newly formed  
 159 lateral etching front forces the finger to progress laterally. This enlargement of the fingers is  
 160 visible in LEEM (fig. 3(b)) and AFM images (fig. 4(a)). This forced lateral spreading gives  
 161 rise to a destabilization of the finger: it splits laterally in two parts with the occurrence of  
 162 a newly exposed SiO<sub>2</sub> BOX layer in the middle. (iv) This SiO<sub>2</sub> layer is in turn the place  
 163 for preferential etching at the triple line. When this SiO<sub>2</sub> layer in the middle is completely  
 164 etched, the two Si fingers meet again and form a flattened structure that encapsulates  
 165 the remaining SiO<sub>2</sub> BOX layers that are protected against further fast etching. When the  
 166 splitting in two parts of the Si fingers does not occur, no elliptic SiO<sub>2</sub> layer is formed and  
 167 another scenario with direct encapsulation of one SiO<sub>2</sub> BOX stripe occurs (see (v) in fig.  
 168 4(c)). This last scenario is clearly put in evidence in the unzipping process of Si fingers as  
 169 detailed in the following.

170 *b. Unzipping of Si fingers* Figure 5(a) shows a sequence of LEEM images at 1370  
 171 K. We can observe a local anomaly at the reaction front edge: the triangular SiO<sub>2</sub> BOX  
 172 layer is locally destabilized and this event suddenly generates a free SiO<sub>2</sub> layer that seems to

173 detach and propagate at high velocity ( $210\pm 10 \text{ nm}\cdot\text{s}^{-1}$ ) in the direction opposite to the front.  
 174 To understand this process we have performed an *ex situ* analysis of the surface morphology  
 175 by AFM. Fig. 5(c) shows an elongated silicon finger away from the front edge ( $\sim 10 \mu\text{m}$ )  
 176 which is hollowed out in the middle. A  $\text{SiO}_2$  BOX layer is clearly observed at the bottom of  
 177 this hollow as a very flat area surrounded by a Si rim and delimited by lateral trenches in  
 178 the oxide layer (see height profile on fig. 5(c)). These very characteristic features of the  $\text{SiO}_2$   
 179 BOX layer, etched locally by Si, have already been observed in the context of conventional  
 180 SOI dewetting [23 and 39] and are found here everywhere at the front edge demonstrating  
 181 unambiguously that the  $\text{SiO}_2$  BOX can be present far away from the front. The proposed  
 182 scenario is the following: The Si fingers formed by SOI dewetting locally etch the BOX  
 183 layer on the lateral sides. When a Si finger reaches the Si handle wafer, the  $\text{SiO}_2$  BOX  
 184 layer may become encapsulated (see scenario (v) in fig. 4(c)) preventing further etching.  
 185 This process is highly stabilized when the front recedes in the  $\langle 100 \rangle$  direction resulting in  
 186 the formation of extremely long  $\text{SiO}_2$  BOX stripes ( $> 30 \mu\text{m}$ ) encapsulated into straight Si  
 187 fingers. Contrary to conventional dewetting of Si/ $\text{SiO}_2$ , the encapsulation of a  $\text{SiO}_2$  layer  
 188 inside a Si structure prevents the dewetting of the Si fingers (fig. 5(b)-(1)). However if the  
 189 dewetting front is destabilized and a finger detaches from the SOI layer edge (2), then a  
 190 new triple line Si/BOX/vacuum appears. Lateral shedding of Si by dewetting is promoted  
 191 (3). This process unzips the Si finger from the middle (hollowed Si finger) and creates two  
 192 lateral rims of Si (4). Simultaneously the freshly exposed  $\text{SiO}_2$  BOX layer is continuously  
 193 etched on the lateral sides giving the impression of the propagation of a  $\text{SiO}_2$  layer at the  
 194 surface (5).

195 *c. Si ring formation* Figures 3(b) and 6(a) address a scenario occurring at slightly  
 196 lower temperature (1300 K). At this temperature the width  $W$  at the front of the freshly  
 197 exposed  $\text{SiO}_2$  BOX layer is about  $2 \mu\text{m}$  (dashed lines in fig. 3(a)) whereas it is about  $0.9$   
 198  $\mu\text{m}$  at 1370 K. The width change arises because the activation energy for dewetting is lower  
 199 ( $2.4 \text{ eV}\pm 0.5 \text{ eV}$ ) than for etching ( $4.0\pm 0.5 \text{ eV}$  as described previously). Therefore the Si  
 200 fingers formed by dewetting are much longer and have now enough time to destabilize by  
 201 a Rayleigh-Plateau type instability. However together with the usual formation of 3D Si  
 202 islands, we also observe the formation of Si rings exposing in the middle a remaining  $\text{SiO}_2$   
 203 BOX layer (see circles in fig. 3(b) and ref. [40]). This is also clearly seen by AFM (fig.  
 204 6(a)). Then this BOX layer in the middle of a Si ring is etched progressively and the ring

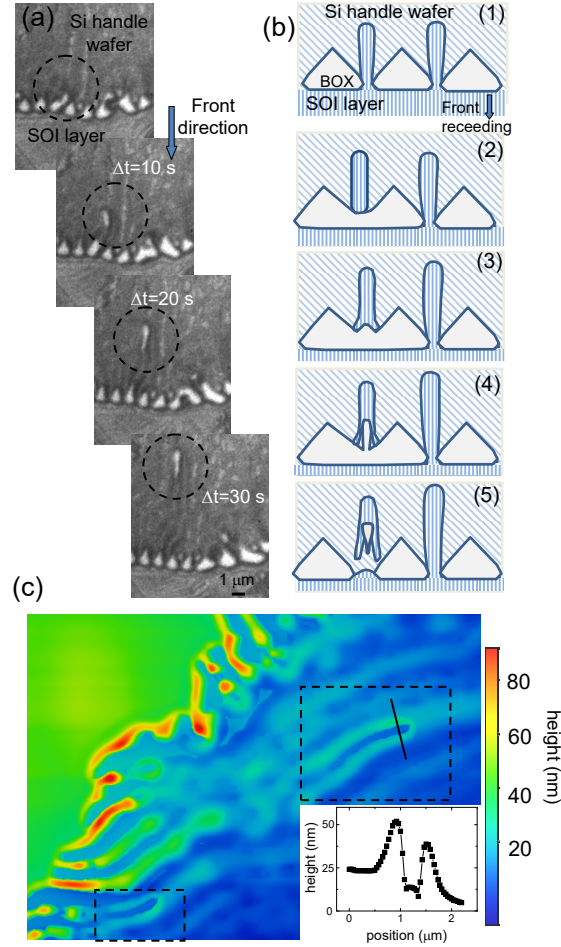


FIG. 5. (a) LEEM image sequence of Si/SiO<sub>2</sub> BOX front at 1370 K. Black dashed circles show the occurrence of a defect at the front that generates the linear propagation of a new front of SiO<sub>2</sub> BOX layer decomposition in the direction opposite to the dewetting front. (b) Scheme of the unzipping scenario of SOI finger with encapsulated SiO<sub>2</sub>. The finger is destabilized at the front side. This event allows for the lateral dewetting of Si and splits the finger into two parts. This process progresses all along the finger over tenth of microns (unzipping process). Simultaneous etching of the newly exposed SiO<sub>2</sub> BOX layer. (c) AFM image ( $16 \times 10 \text{ } \mu\text{m}^2$ ) showing the morphology of this unzipping process (black dashed areas). Inset: profile of a silicon finger hollowed out in the middle (black line): Si lateral rim, trenches in the the SiO<sub>2</sub> layer at the contact line with Si and flat area of BOX in the middle.

205 shape smoothens giving a final rough Si surface morphology. We propose a scenario similar  
 206 to the one described for Si fingers (fig. 4(c)) but adapted to 3D islands: (i) The 3D Si islands

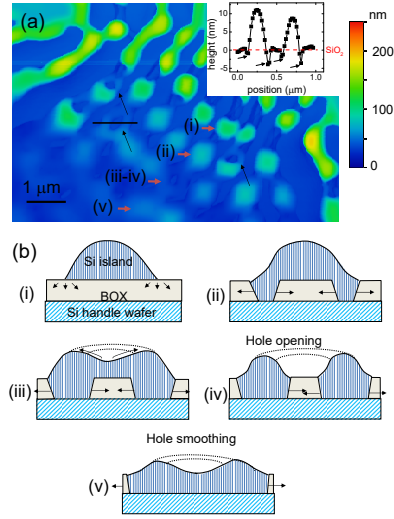


FIG. 6. (a) AFM image of the dewetting/reaction front (1300 K) obtained after quenching to RT. Elongated Si fingers are observed and agglomerate into 3D islands. The islands are unstable against Si rings formation (black arrow). Inset: profile of a circular hole (black line in the image) exposing a remaining SiO<sub>2</sub> BOX layer inside (BOX surface: red dashed line). Black arrows show the trenches in the BOX layer formed by local etching at the Si/SiO<sub>2</sub> contact lines. (b) Scenario of ring formation: (i) Si islands formed by dewetting and Si fingers. (ii) Local breaking through the SiO<sub>2</sub> layer and contact with the Si handle wafer. (iii) Radial progression of the reaction front and Si mass shedding from the center of the island. (iv) Opening of a hole into the center exposing the remaining SiO<sub>2</sub> BOX layer. (v) Etching of the SiO<sub>2</sub> BOX layer and spreading/smoothing of the Si layer.

207 formed by SOI finger dewetting instability [23 and 37] expose the BOX layer to vacuum. The  
 208 circular contact line between the Si islands and the BOX layer is the place for preferential  
 209 etching of the BOX layer. (ii) When the BOX layer is locally completely etched, the SOI  
 210 layer and Si handle wafer are in contact and then the etching front progresses radially as for  
 211 Si fingers. (iii) This process favors a mass transfer of Si from the center to the edge. (iv)  
 212 This Si shedding destabilizes the compact island shape into a ring and a circular BOX layer

213 appears in the center as it was protected by the 3D island. This observation is similar to the  
214 one obtained in the context of liquid Si droplets onto SiO<sub>2</sub> (quartz) forming spontaneously a  
215 liquid Si torus [41]. (v) Then the inner SiO<sub>2</sub> layer progressively disappears by lateral etching  
216 and when it is completely etched the Si morphology smoothens.

## 217 IV. CONCLUSION

218 We have shown by *in situ* LEEM and *ex situ* AFM that the Si/SiO<sub>2</sub> interface in ul-  
219 tra thin SOI system can lead to different structures/morphologies depending on annealing  
220 conditions. The competition between (de)wetting and Si+SiO<sub>2</sub> → 2 SiO<sub>g</sub> reaction kinetics  
221 makes possible to achieve steady state regimes where the dewetting front and the etching  
222 front coexist in a narrow space region. These regimes may create peculiar structures such  
223 as 1D thin SiO<sub>2</sub> BOX stripes encapsulated into crystalline Si fingers or Si rings with a SiO<sub>2</sub>  
224 BOX layer in the center. The formation of these structures follow different scenarios where  
225 the localization of the etching at the contact line between Si and SiO<sub>2</sub> and mass transfers  
226 induced by Si/SiO<sub>2</sub> wetting properties play key roles. Small modifications at the front edge  
227 may also lead to instabilities such as the fast unzipping of Si fingers with encapsulated SiO<sub>2</sub>  
228 BOX stripes. This analysis of the front dynamics is completed with a quantitative study of  
229 the energetics of the process. We show that dewetting and etching reaction are thermally  
230 activated with an activation energy respectively of 2.4±0.5 eV and 4.0 ±0.5 eV. To conclude,  
231 these results propose a general picture of the dynamics of Si/SiO<sub>2</sub>/Si interfaces at high tem-  
232 perature in the limit of a thin SiO<sub>2</sub> layer (≤ 8 nm). We believe these results may initiate  
233 new approaches to fabricate specific structures based on SOI technology [42 and 43] and to  
234 prevent SOI dewetting processes by encapsulation approaches.

## 235 V. SUPPLEMENTARY MATERIALS

236 See supplementary materials for the complete movies of the dewetting and reacting pro-  
237 cesses.

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