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Local laser induced rapid thermal oxidation of SOI substrates

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Abstract

A direct method for lateral patterning of silicon on insulator (SOI) films with sub-μm resolution is presented. This method is based on rapid thermal oxidation induced by a focused laser beam. By focusing the cw light of an argon ion laser at a wavelength of 458 nm (514 nm) we achieve a diffraction limited laser spot of 315 nm (350 nm). The laser spot is scanned over the surface of a 15–100 nm thick silicon film in ambient air. Above a critical laser power rapid local oxidation of the entire silicon film at the exposed sample spot is observed. Below this threshold power even within longer time scales no changes of the sample surface are detected. AFM measurements of laser written oxide lines show line widths down to 200 nm. Both this high spatial resolution and the dynamics of the oxidation process near the threshold power are attributed to nonlinear effects of the absorption and heat conduction in the sample. Model calculations show that the temperature profile can be even narrower than the laser spot diameter. The oxidation is related to an unstable temperature distribution in the exposed sample, caused by a self amplifying heating. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Oxidation; Silicon on insulator; Laser induced

1. Introduction

Since many years laser annealing of semiconductors has become a well established technique for very different purposes [1]. Beside annealing of implanted semiconductors for healing the implantation damage and recrystallisation of thin films, laser induced or at least enhanced oxidation of silicon is one of the most interesting applications. Pulsed lasers are used as well as cw lasers in the whole spectral range of infrared, visible and UV radiation. For many applications low temperature and rapid localized processes are of utmost interest in order to preserve the samples from thermal stress. Therefore contributions by non thermal, photonic oxidation were investigated [2]. In all these works no special emphasis on lateral spatial resolution was made. In our work we study the annealing of thin silicon films using a cw laser with the special purpose of a high spatial resolution. Previous model calculations of the temperature distribution during annealing of silicon with a cw laser have already shown essential contributions of nonlinear effects resulting in a narrowing of the temperature profile [3]. However, due to varied optical properties in the buried oxide and the thermal peculiarities of thin films the SOI layer system behaves qualitatively completely different.

2. Experimental results

We use cw light of an argon ion laser at a wavelength of 458 nm (514 nm) which we focus onto a 15–100 nm thick silicon film. Employing a high numerical aperture lens system (N.A. 0.95) we achieve a diffraction limited laser spot of 315 nm (350 nm)

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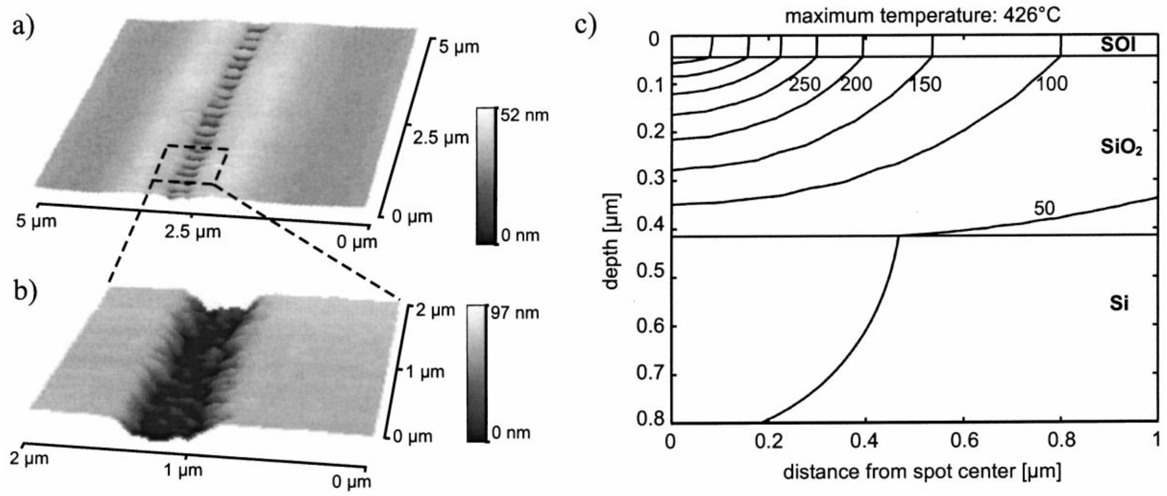

Fig. 1. AFM-measurements of laser written oxide lines on SOI directly after laser processing (a) and after removal of the oxide by wet etching in HF (b), (c) calculated temperature distribution in a cross section of the sample with the layer sequence: SOI film–buried oxide–silicon substrate.

FWHM. Samples are treated at room temperature and in ambient air. With a x–y-translation stage the sample is continuously moved under the laser spot. An auto-focus system provides a constant spot size during the writing process. Scanning speeds in the range between 50 and 2 µm/s are studied. We use several different SOI substrates with 15–100 nm doped and undoped silicon layer on top of a buried oxide layer with a thickness of 195 and 370 nm and the bulk silicon substrate below the oxide, see schematic cross section in Fig. 1(c).

In all our experiments on SOI we observe that for laser powers below a critical threshold value the sample surface does not change. However, above this critical laser power a rapid local oxidation in the SOI layer occurs. Fig. 1(a) shows an AFM picture of a laser written line on SOI directly after laser treatment. The regular sequence of elevations and valleys originate from a pulsating oxidation, which occurs mainly for laser powers near the threshold value independent of the scan speed. We remove the oxide in the center of the laser trace by etching in diluted HF (see Fig. 1(b)) and measure the width of the oxidized region by AFM. For 458 nm laser light at a power just above the critical value line widths down to 200 nm were obtained which is well below the spot diameter.

With increasing laser power the line width increases. We find that the oxidation is an all-or-nothing process, i.e. when oxidation takes place then the entire silicon layer thickness is affected. Within the confidence level we find no dependence of the line width and the threshold power on the scan speed in the investigated range [4]. This can be explained by the rapidity of the oxidation in conjunction with a self limiting mechanism caused by an abrupt drop of absorption when silicon is oxidized.

3. Model calculations

In order to explain the high spatial resolution and the dynamics of the oxidation process near the threshold power we have performed model calculations of the temperature rise for low laser powers, i.e. below the oxidation threshold. For a stationary laser spot the temperature $T(r, z)$ at the distance r from the center of the laser spot and at the depth z obeys the static heat equation

$$\nabla[\kappa(T)\nabla T(r,z)] = -[1-R(T)]I_0\alpha(T)\exp\left(-\frac{r^2}{w^2}\right) \times \exp\left(-\int_0^z \alpha(T(r,z'))dz'\right) \quad (1)$$

with temperature dependent heat conductivity $k(T) = k_0 T_0/T$, reflesction coefficient $R(T)$ and absorption coefficient $\alpha(T) = \alpha_0 \exp[\beta \cdot (T - T_0)]$ [3]. The right hand side of Eq. (1), the heat source, contains the intensity distribution $I_0 \exp(-r^2/w^2)$, where w is an effective width consisting of the width of the laser profile and the diffusion length of the photo excited electrons [5], which transfer the energy from the laser to the lattice. At the interface between silicon and buried oxide continuity conditions for the heat flow hold. Compared to bulk silicon the lateral heat conductivity in the thin silicon films of SOI is significantly reduced due to phonon surface scattering [6]. The vertical thermal conductivity is reduced by the buried oxide layer, which does not absorb laser light.

Fig. 1(b) shows the calculated temperature distribution in a cross section of a SOI sample during illumination. With an absorption length significantly larger than the SOI film thickness most of the laser light penetrates the SOI film and the buried oxide layer and is absorbed in the silicon substrate. There the energy can easily dissipate by heat diffusion. So the heating is essentially localized in the top layer. The dashed lines in Fig. 2(a) represent the radial surface temperature in bulk silicon for laser powers of 140 and 149 mW respectively. One can see the large rise in temperature and the narrowing of the temperature profile for higher temperatures compared to lower ones caused by the temperature dependent material parameters $k(T)$, $R(T)$ and $a(T)$. The temperature profile for a SOI sample (full line) is even narrower than that of bulk silicon. However, most interesting is the following qualitatively different effect. In Fig. 2(b) the maximum temperature in the center of the laser spot is plotted as a function of the laser power. The full line shows the normal behaviour, i.e. temperature increases monotonically with increasing laser power, whereas the dotted line represents unstable solutions of the heat equation. This solutions are a border of stability and separate two regimes in the system.

1. A stable low temperature regime with low absorption in the SOI layer;
2. A high temperature regime where the increase of absorption with the temperature causes a self amplification of the heating. The system would end in a temperature far above the melting point with the whole laser power being absorbed in the top layer. In reality it ends in a rapid melting or oxidation of the SOI layer.

The substantial results are, that above a critical laser power (here 32 mW) no stable temperature below the melting point exists and the stable temperatures for lower laser powers are all below a relatively low value (here 450°C). This instability describes our experimental results of the sharp transition from a regime without any change of the surface to a rapid oxidation process.

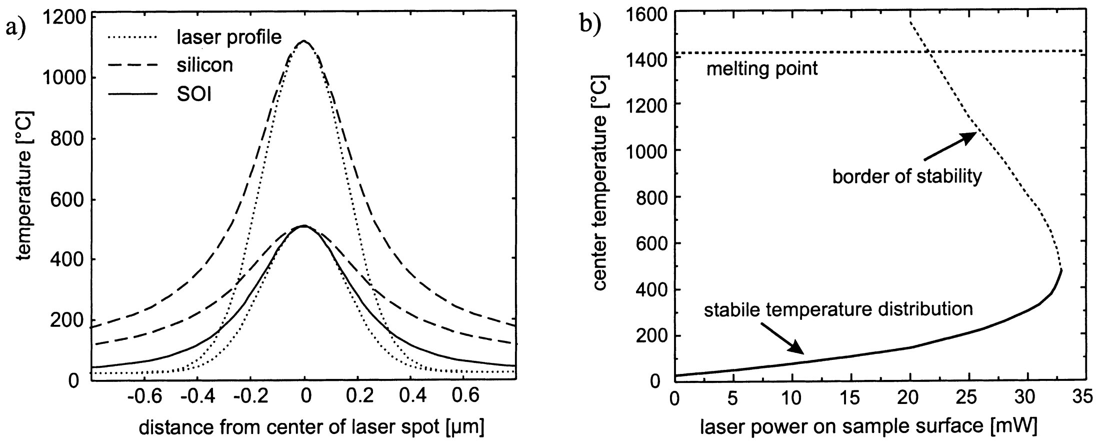

Fig. 2. (a) Calculated temperature profile in a 45 nm thick SOI film at a laser power of 32 mW (wavelength 514 nm) (full line) and in bulk silicon at 140 and 149 mW laser power (dashed line) the dotted line shows the width of the laser profile, normalized to the maximum temperature, (b) phase diagram: full line shows the maximum temperature (at $r = 0$, $z = 0$) for the real temperature distributions, the dotted line indicates unstable solutions of the heat equation.

4. Conclusion

We have developed a novel method for direct resistless patterning of thin film SOI. The method is based on rapid local oxidation induced by heating with a focused cw laser beam. A combination of nonlinear effects cause a sharp transition from stable temperature distributions with maximum temperatures below about 450°C to a rapid self amplifying heating resulting in local oxidation of the entire SOI film. Due to the drop of absorption the temperature also decreases after oxidation. Because of this self limiting effect, adjacent areas of the SOI film are not affected by the heating and global sample heating is suppressed. Laser written oxide lines reveal excellent electrical isolation properties. Therefore, in-plane-gate, devices can be fabricated using these laser formed lines as gate isolation [4].

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