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Pattern-induced ripple structures at silicon-oxide/silicon interface by excimer laser irradiation

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Ripple structures by KrF excimer laser irradiation have been observed on a silicon surface capped with a thin layer of patterned silicon oxide. The ripples are highly dependent on the patterns of the silicon oxide. They are centered and enhanced at the boundaries of the opened windows, forming a radial-wavelike structure. The formation of the ripples is attributed to the combined effect of surface stress, surface scattered wave and boundary effects. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1496141]

As the gate length of metal–oxide–silicon (MOS) transistors continues to shrink below 0.10 μm, the vertical and lateral dimensions of p-n junction regions must be scaled down as well to maintain device performance and control short-channel effects. Conventional ion implantation and thermal annealing is difficult to obtain abrupt, highly doped, and ultrashallow junctions. Thus, new alternative processes are being explored and developed. Among the new processes for shallow junction fabrication, laser doping, and silicidation technology is regarded as a revolutionary approach due to its high local heating power and nanosecond short pulse duration. It enables the formation of box-shaped junctions with unequaled shallowness and low sheet resistance.[1] A large amount of effort has been made to the development of this technology.[2–5] On the other hand, laser-induced damage of solids has been an area of both theoretical and experimental interest ever since the development of the laser itself. Ripples, i.e., gratinglike patterns or laser-induced periodic surface structures, have been observed and studied on the surface of various metals, semiconductors, dielectrics, and polymers for more than three decades.[6–9] The basis of the currently accepted theory of ripples is the interference of the incident lights and some form of "surface scattered wave." The ripples appear as the result of nonlinear positive feedback growth process initiated by the light scattering due to the random variation of any optically significant surface property.[8]

In laser doping and silicidation process, silicon oxide is often used as a hard mask or cap layer. In this letter, we report pattern-induced ripple structures at silicon-oxide/silicon interface by excimer laser irradiation.

The samples used in this work are phosphorus-doped n-type (100) silicon wafers with a resistivity of 6–9 Ω cm. Silicon oxide with a thickness of 100 nm was deposited on the silicon wafer by plasma-enhanced chemical vapor deposition at 150 °C using silane $[SiH_4/N_2\ (95\%)]$ and nitrous oxide (N_2O). Then oxide patterns were generated by lithography and etching process. Figure 1 shows the optical microscope observation of the oxide-capped sample. A Lambda Physik KrF excimer laser (LPX50) with a wavelength of 248 nm and a pulse duration of approximately 23 ns was used. The unpolarized laser beam perpendicularly irradiated the samples in air after passing through a homogenizer and being focused by a quartz lens.

Figure 2 shows the optical microscope observation of samples after a single pulse irradiation with a laser fluence of 430 mJ/cm^2. For comparison, observation was provided in Fig. 3 for samples after a single pulse irradiation with a laser fluence of 750 mJ/cm^2.

As shown in Fig. 2(a), local ripples can be produced at oxide-capped silicon area. The ripples exist only at rectangle-window corners and high window density areas, where surface stress is believed to be high. It is similar to the formation of defect-induced ripple structures, in which the defects become the surface wave center and produce local ripples. When laser fluence increases, more ripples are produced around the opened windows, as illustrated in Fig. 3(a). The ripples, centered at the window boundaries, perpendicularly run away from the boundaries. The amplitude of ripples at rectangle-window corners and high window density areas is also much higher. Since there is melting under laser irradiation, there is no more crystal orientation in Si substrate

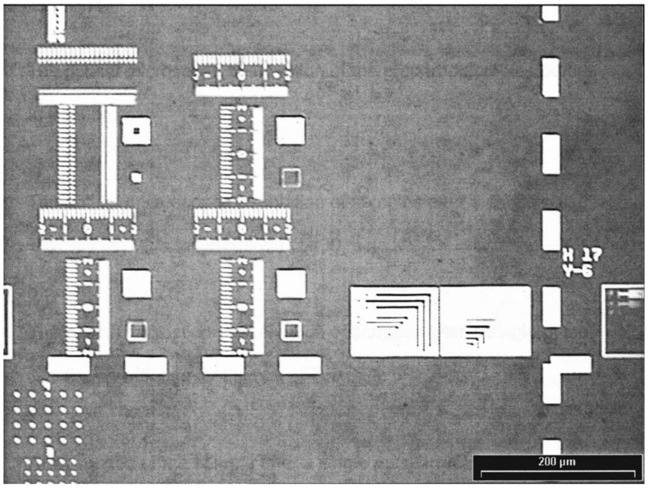

FIG. 1. The optical microscope observation of the prepared samples before irradiation.

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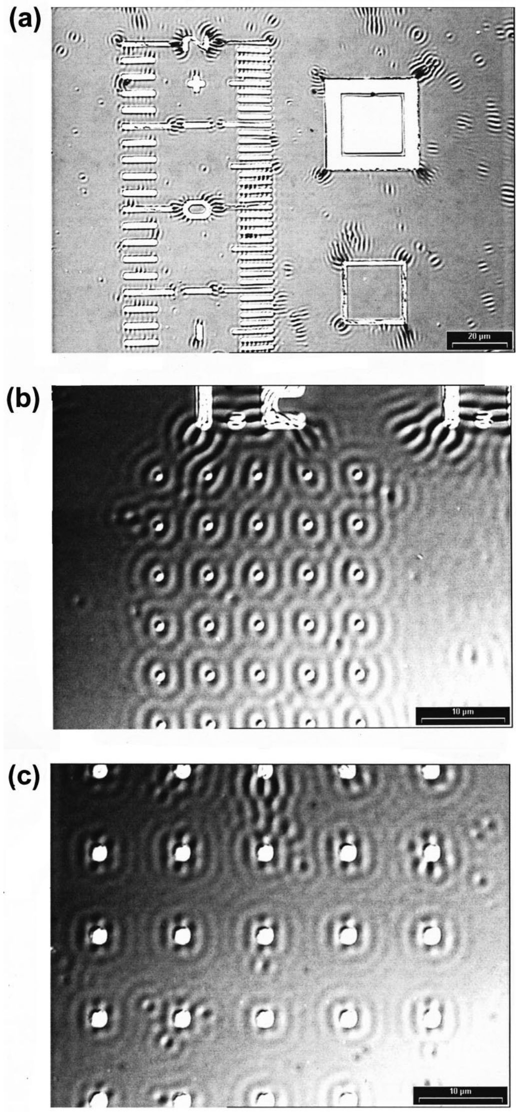

FIG. 2. The optical microscope observation of samples after a single pulse irradiation with a laser fluence of 430 mJ/cm^2. The scale bar shows 20 μm in (a) and 10 μm in (b) and (c).

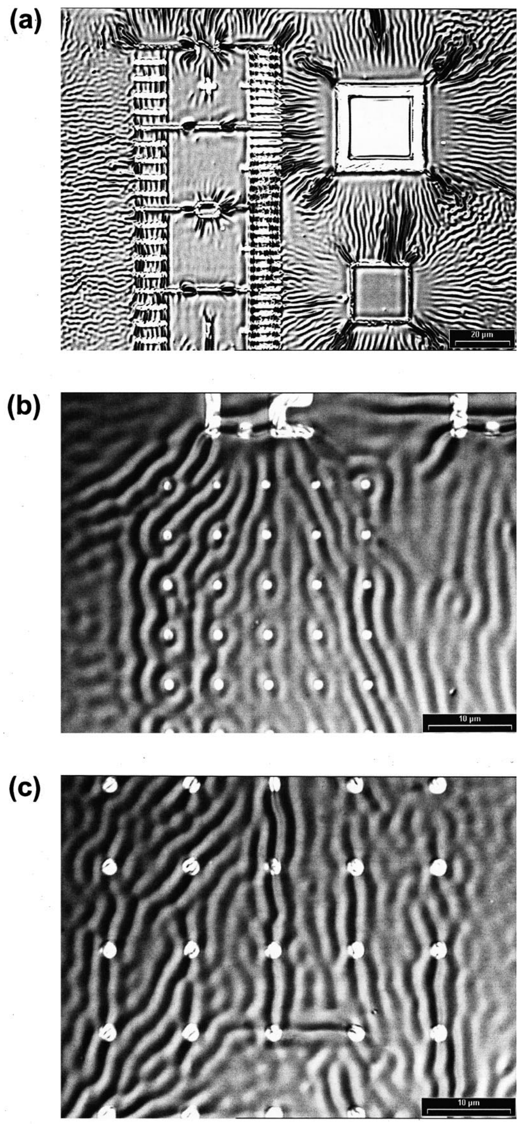

FIG. 3. The optical microscope observation of samples after a single pulse irradiation with a laser fluence of 750 mJ/cm^2. The scale bar shows 20 μm in (a) and 10 μm in (b) and (c).

and the direction of heat flow is radially inward to boundaries. Therefore, it is believed that the ripples are not dependent on laser polarization and crystal structure of the substrate. Their alignment only depends on the local surface morphology or the patterns, which differs greatly from the previous observation of periodical ripples with no orientation preference.[10] Thus, we refer to such type of ripples as pattern-induced ripples. They are the domain ripples near boundaries while periodical ripples[10] become dominant at the distant area from boundaries. During KrF excimer laser irradiation, the laser–material interaction occurs at the silicon-oxide/silicon interface since silicon oxide is transparent to the laser light at the wavelength of 248 nm. Due to the existence of silicon oxide, the light reflection is greatly weakened at the silicon-oxide/silicon interface compared with the light reflection at the air/silicon interface. The equivalent reflectivity of the silicon-oxide/silicon system (air/silicon-oxide and silicon-oxide/silicon interfaces) will be smaller than that of the bare silicon surface, which means more light is absorbed in the oxide-capped silicon. It is confirmed by measuring the reflectivity using a spectrophotometer. The reflectivity of the oxide-capped silicon and the bare silicon surface is 46.8% and 63.0% respectively at 248 nm. Therefore, the oxide-capped silicon will melt first under laser irradiation. Then, the melting front advances to the bare silicon in the window. There is a temperature gradient perpendicular to the window boundaries. Specifically, a sharp temperature difference exists at the window boundaries, which will induce a high stress. Moreover, the bare silicon surface has a higher cooling coefficient as compared with the oxide-capped silicon due to the existence of silicon oxide. Thus, the bare silicon in the window will always cool faster, which also generates a temperature gradient. Because of these boundary effects, flow patterns with directions of heat flow are recorded at the silicon-oxide/silicon interface after laser pulse ends.

As shown in Fig. 2(b), some circular ripples can be observed around the dots with a diameter of 1.2 μm. The circular ripples centered at the dots are just identical with the defect-induced ripple structures. Since these dots are small and comparable with local defects, they act as local defects

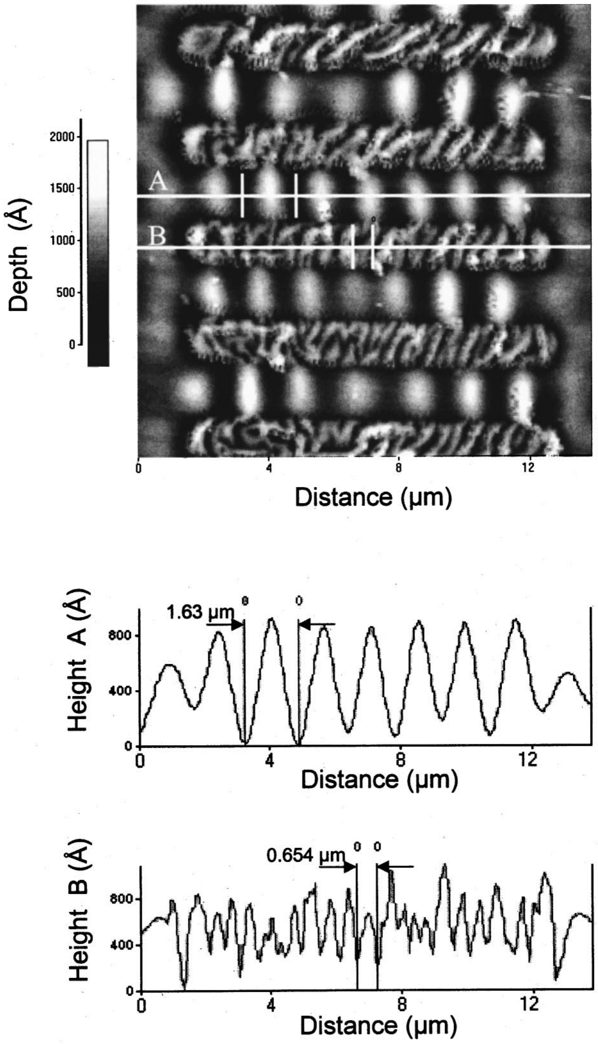

FIG. 4. AFM images of the sample after a single pulse irradiation with a laser fluence of 500 mJ/cm^2 and silicon oxide removal.

to be the surface wave center and induce local ripples. The same circular ripple structures are also found around small dots with the diameter up to 1.8 μm. Thus, the existence of surface scattered wave is confirmed.

As shown in Fig. 2(c), circular ripples combined with pattern-induced ripples are formed around the dots with a diameter of 2 μm. Since the dots have a larger size than those in Fig. 2(b), the area and heat volume of bare silicon is big enough to have an impact on the melting of the oxide-capped silicon. Boundary effects will gradually become dominant in the ripple formation. As illustrated in Fig. 3(c), fully developed pattern-induced ripples are formed in the dot matrix at higher laser fluence, since the boundary effects are enhanced at higher-energy density.

From the observation in Figs. 2 and 3, it can be concluded that the formation of pattern-induced ripple structures is due to the combined effect of surface scattered waves, surface stress, and boundary effects. The threshold energy of ripple formation is also studied in this work. It is found that the threshold laser fluence on silicon capped with patterned oxide (oxide with opened windows) is 380 mJ/cm^2, while the threshold on silicon capped with whole layer oxide (oxide without patterns) is 500 mJ/cm^2. Thus, the threshold energy is reduced due to the existence of oxide patterns.

Figure 4 shows the atomic force microscopy (AFM) images on the silicon surface. The oxide layer was removed by diluted HF solution. It is found that the defined patterns combined with fully developed ripples have been recorded at the silicon surface. Two groups of ripples can be observed: (1) Pattern-induced ripples perpendicularly run across the windows. From the cross-sectional topography, their average period is around 1.6 μm and height around 80 nm. (2) Small parallel ripples with a certain angle from the boundaries are formed and confined in the window. Their average period is around 50 nm, which is much smaller than that of the pattern-induced ripples since the ripple periodicity is found to increase linearly with increasing silicon-oxide thickness.[11] Their height is identical with that of the pattern-induced ripples, which indicates resonance of two groups of ripples during their formations. The cross-sectional topography along with the line B clearly shows a sudden surface morphology change at the window boundary, which suggests an abrupt change of surface melting process.

From our experiment, it is noticed that ripple structures can be easily formed on the silicon surface within the fluence range used for laser doping and silicidation. In MOS technology, the ripples in the contact windows can result in serious problems in the following metallization processes. The depth of *p-n* junctions formed under the rough silicon surface will also not be uniform. Furthermore, the rough silicon surface due to ripples can result in junction spiking.

In conclusion, pattern-induced ripple structures by KrF excimer laser irradiation have been observed at the silicon-oxide/silicon interface. The patterns introduce local stress and abrupt changes of surface optical properties. During laser irradiation, pattern-induced ripples can be formed at low laser fluences due to the combined effect of surface scattered waves, surface stress, and boundary effects.

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