Japanese Journal of Applied Physics
Vol. 27, No. 10, October, 1988, pp. L1935–L1937

In Situ Observation of Pulsed Laser Doping

Toshiyuki Sameshima, Hisashi Tomita and Setsuo Usui

Sony Corporation Research Center, 174, Fujitsuka-cho, Hodogaya-ku, Yokohama 240

(Received June 29, 1988; accepted for publication September 16, 1988)

Transient conductance measurements were used to study the rapid process of pulsed laser doping of silicon film. The use of a thin silicon-on-sapphire (SOS) film made it possible to measure the movement of the liquid-solid interface during melting and regrowth and to determine the point at which the carrier generation of dopant atoms diffused in the molten silicon begins. The results of the transient conductance measurements revealed that the recrystallization of molten silicon and the activation of dopant atoms diffused in the molten silicon occurred simultaneously.

KEYWORDS: laser doping, transient conductance measurement, time-resolved optical reflectivity measurement, excimer laser, pulsed laser-induced melt and regrowth

§1. Introduction

Ultrashallow junctions have received much attention recently because submicron gate metal-oxide-semiconductor (MOS) transistors require a source and a drain whose depth is in the order of 0.1 μm. In order to fabricate such a shallow junction, a laser doping technique using a pulsed UV excimer laser has been developed.[1-3] For laser doping, dopant atoms are diffused quickly with a diffusion coefficient of 10^{-4} cm^2/s from the surface in the molten region induced by the laser irradiation. With this technique, no high-energy ion beam is necessary to incorporate dopant atoms into the substrate, therefore, it can be used to dope a silicon-on-insulator (SOI)[4] device as well as to dope a bulk silicon. We have previously reported a computer simulation of boron diffusion and the formation of boron profiles in laser doping, and found a relation between the junction depth and the melt depth.[5] The laser doping mechanism, however, has not yet been determined experimentally.

In this paper, we report for the first time the in situ observation using transient conductance measurements of pulsed laser doping. Galvin *et al.* made transient conductance measurements using bulk silicon in order to examine the characteristics of the melt-regrowth process induced by pulsed ruby-laser irradiation.[6] This method, however, had a problem in that large photogenerated carriers produced in bulk silicon prevented the measurement of the advancing melt front. In order to reduce the photogenerated carriers, we used a thin silicon-on-sapphire (SOS) film. This paper reports the characterization of the rapid melt and regrowth and the laser doping process.

§2. Experlmental

Figure 1 shows a schematic diagram of the experimental system. Irradiation was provided by a pulsed XeCl-308 nm excimer laser ($\tau=30$ ns full-width at half maximum) in air. The sample was entirely irradiated with the laser beam focused by a lens whose beam spot was 2.3 mm × 6 mm at the surface. The incident energy density was varied by density filters. The transient current during laser treatment was measured across the load resistance by a high-speed storage oscilloscope. The duration of the melt at the sample surface was determined by measuring the time-resolved optical reflectivity using an Ar-514.5 nm laser beam as a probe light. The transformation of silicon from a solid to a molten state lead to the higher reflectivity of the surface associated with the metallic liquid phase.[7] The Ar-laser beam was focused by a lens on the center of the sample with a beam diameter of 0.1 mm. The reflection was detected by a high-speed photodiode and the change of reflectivity was traced by a storage oscilloscope. The time resolution of the measurement system for the transient conductance and the time-resolved optical reflectivity was 8 ns.

For accurate measurements of transient conductance during the laser irradiation, we used an undoped 500 nm-thick SOS film with an orientation of (100) and a resistivity of 100 Ωcm. The SOS film was patterned into 1 mm-wide stripes; 2.3 mm-gapped Al electrodes with a width of 3 mm were formed on the silicon stripes by lithography. The sample was then placed in a chamber for radio-frequency glow discharge (rf-GD) and a boron film was deposited on the surface by decomposition of B_2H_6 diluted to 1% with Ar gas. After being taken out

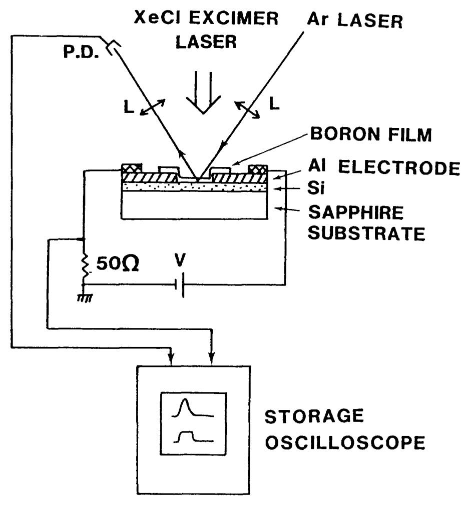

Fig. 1. Schematic diagram of sample and measurement apparatus for transient conductance and time-resolved optical reflectivity.

from the chamber, the sample was connected to a load resistance of 50 Ω and a bias voltage of 10 V was applied.

The transient sheet conductance [$C(t)$] is obtained using the equation:

$$C(t)=\frac{I(t)}{[V-(R_l+R_c)I(t)](W/L)}, \quad (1)$$

where $I(t)$ is the transient current, R_l the load resistance of 50 Ω, V the bias voltage of 10 V, R_c the circuit resistance of 1.8 Ω (resistance of Al electrodes plus contact resistance), and W/L the geometric factor of the sample of 1 mm/2.3 mm.

§3. Results and Discussion

Prior to laser doping, the transient conductance and the time-resolved optical reflectivity were measured for a 500 nm-thick SOS film, on which a dopant film was not deposited, in order to obtain the melt-regrowth characteristics. Figure 2 shows the conductance transient and optical reflectivity change with time during and after irradiation on the SOS film at an energy density of 1.2 J/cm^2. High optical reflectivity persisted for 300 ns. During the same period, the conductance first increased with time and then decreased after reaching a maximum value at 130 ns. This means that silicon melted at the surface and the melt front advanced into the film and then moved back to the surface.

Figure 3 shows the conductance transients of the SOS film for laser energy densities between 0.67 and 1.35 J/cm^2. The conductance increased with increasing the laser energy density. The broken curve is a conductance transient for the threshold melting energy density (0.67 J/cm^2), which was determined as the maximum laser energy density at which the high optical reflectivity associated with molten silicon did not appear. This conductance transient was caused by photogenerated and thermally generated carriers induced by the irradiation in the solid silicon. However, at higher energies than 0.67 J/cm^2, conductance transients of molten silicon were much larger than that depicted by the broken line, as can be seen in Fig. 3. Thus, the conductance transients for molten silicon were measured exactly using an SOS film. Figure 3 also represents the depth of the molten layer versus time, which is deduced from the hypothesized conductivity of molten silicon (12000 S/cm).[8] Under irradiation at 1.35 J/cm^2, the melt front advanced at a velocity of ~5 m/s and the melt depth reached 440 nm. Afterwards, molten silicon recrystallized at a velocity of ~4.5 m/s.

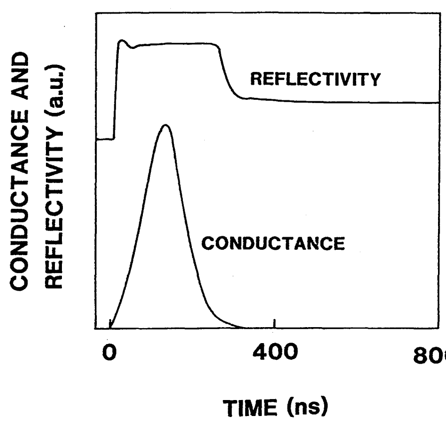

Fig. 2. Conductance and optical reflectivity versus time for an SOS film irradiated with a pulsed XeCl excimer laser at an energy density of 1.2 J/cm^2.

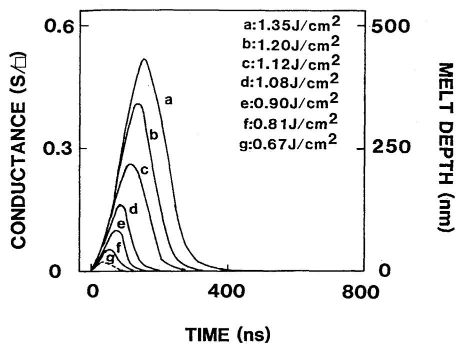

Fig. 3. Conductance versus time for an SOS film at energy densities between 0.67 and 1.35 J/cm^2. The depth scale was derived using the conductivity of molten silicon (12000 S/cm). The broken curve represents the conductance of the solid silicon irradiated at melting threshold energy.

Next, we measured the transient conductance for an SOS film on which a 50 nm-thick boron film was deposited for laser doping. Deposition of the boron film reduced the optical reflectivity of the surface from 62% (bare-silicon) to 50% at 308 nm by the antireflection effect and reduced the threshold melting energy from 0.67 J/cm^2 to 0.50 J/cm^2. Figures 4(a) and 4(b) shows the conductance transients during laser doping using a single pulse irradiation for laser energy densities between 0.65 and 1.04 J/cm^2. Figure 4(b) is the vertical expansion of Fig. 4(a). In Fig. 4(a), conductance transients associated with the melt-regrowth process appeared at the first stage in the measurement period. The residual conductance caused by boron doping was measured for each sample after the molten silicon recrystallized, as seen in Fig. 4(a). This result indicates that the boron atoms diffused in the molten region were activated and carriers were generated during the recrystallization process. At the termination of the melt of the silicon film, which was determined by the decrease in the optical reflectivity, the residual conductance ranged from 0.015 S/□ to 0.060 S/□, depending on the energy density of irradiation from 0.65 to 1.04 J/cm^2 as seen in Fig. 4(b). This resulted from the fact that a larger amount of boron atoms was diffused in the molten region and a more deeply doped region was formed at higher energy densities. The conductance after the melt-regrowth of each sample increased monotonously with time and reached a room temperature conductance, which was about twice the value at the termination of the melt; the room temperature conductance of 0.11 S/□ was obtained for the most heavily doped layer formed by a single pulse at 1.04 J/cm^2.

In order to examine whether the activation of diffused boron atoms is completed at the termination of the melt or whether it continues even in solid phase after melt-regrowth, another experiment was carried out as follows. An SOS film, boron-doped with a single pulse irradiation at an energy density of 0.60 J/cm^2, was successively ir-

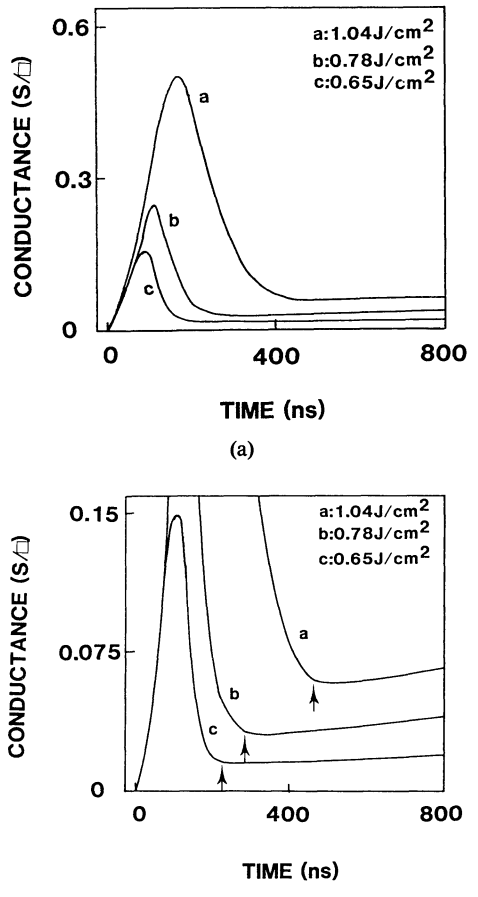

Fig. 4. Conductance versus time during laser doping with a single pulse for energy densities between 0.65 and 1.04 J/cm^2. Figure (b) is the vertical expansion of figure (a). The arrows in Fig. (b) represent the termination of melt.

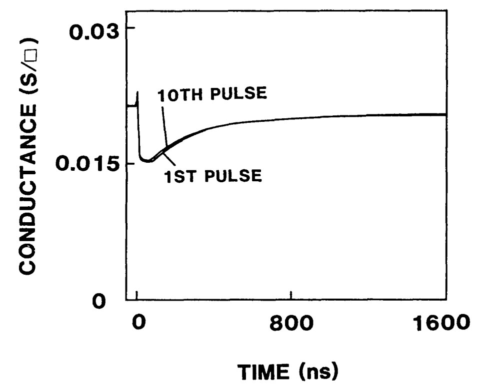

Fig. 5. Conductance versus time for boron doped silicon at the 1st and 10th irradiation with an energy density of 0.45 J/cm^2. A small peak of conductance at the initial stage was caused by the photogenerated carriers.

radiated with 10 pulses at an energy density of 0.45 J/cm^2, which is lower than the melting threshold energy. Figure 5 shows the conductance transients caused by irradiation with the 1st and 10 th pulse at 0.45 J/cm^2. At each irradiation time of the 10 pulses, the conductance changed in similar fashion; it decreased rapidly and afterwards increased gradually to the initial value of 0.021 S/□. No further increase of the room temperature conductance was observed by the laser treatment with 10 pulses at 0.45 J/cm^2. This result indicates that no further activation of boron atoms was effected in the solid silicon by the laser heating. From the results of Fig. 4 and Fig. 5, in laser doping, the diffused boron atoms in molten silicon were activated during the recrystallization process and the activation was completed at the termination of melt. The gradual increase of conductance with time after melt-regrowth, as seen in Fig. 4(b), therefore, can be interpreted as the scattering of carriers by lattice vibration reduced as the silicon film was cooled through heat diffusion to the underlying substrate.

§4. Summary

Through transient conductance measurements we obtained the characteristics of laser-induced melt-regrowth and laser doping of a 500 nm-thick SOS film. Irradiation at 1.35 J/cm^2 caused the melt front to advance at a velocity of ~5 m/s. Afterwards, molten silicon recrystallized at a velocity of ~4.5 m/s. The laser-induced melting of the SOS film coated with a 50 nm-thick boron film caused the conductance of carriers from a boron-doped region, which appeared at the final stage of the melt-regrowth process and then increased as the solid silicon film cooled. This indicates that boron atoms diffused in the molten region were activated during the recrystallization process. The increase of conductance with time after melt-regrowth can be interpreted as the scattering of carriers reduced with decreasing temperature.

Acknowledgements

The authors would like to thank M. Nakagoe and K. Kunisada for their experimental support and Dr. Y. Kawana for the helpful discussions. They also wish to acknowledge the support of Dr. M. Kikuchi.

References

1) T. F. Deutsch, J. C. C. Fan, G. W. Turner, R. L. Chapman, D. J. Ehrlich and R. M. Osgood, Jr: Appl. Phys. Lett. **38** (1981) 144.
2) P. G. Carey, K. Bezjian, T. W. Sigmon, P. Gildea and T. J. Magee: IEEE Electron Device Lett. EDL-**7** (1986) 440.
3) T. Sameshima, S. Usui and M. Sekiya: J. Appl. Phys. **62** (1987) 711.
4) P. Coxon, M. Lioyd and P. Migliorato: Appl. Phys. Lett. **48** (1986) 1785.
5) T. Sameshima and S. Usui: *Proc. MRS on Laser & Particle-Beam Chemical Processing for Microelectronics, 1987,* eds. D. J. Ehrlich, G. S. Higashi and M. M. Oprysko (Material Research Society, Pittsburgh, PA, 1987) p. 491.
6) G. J. Galvin, M. O. Thompson, J. W. Mayer, R. B. Hammond, N. Paulter and P. S. Peercy: Phys. Rev. Lett. **48** (1982) 33.
7) D. H. Auston, J. A. Golovchenko, P. R. Smith, C. M. Surko and T. N. C. Venkatesan: Appl. Phys. Lett. **33** (1978) 538.
8) V. M. Glazov, S. N. Chizhenvskaya and N. N. Glagoleva: *Liquid Semiconductors*, (Plenum Press, New York, 1969) p. 60.