

Laser-induced CVD of doped silicon stripes on SOS and their characterization by piezoresistivity measurements

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ABSTRACT

An argon-ion laser with the visible cw radiation was used to deposit highly doped p-type silicon stripes on (1102) sapphire substrates covered by a 1 μm thick epitaxial silicon layer (SOS). The resistivity of the stripes deposited in an atmosphere of silane with 1% diborane was 0.5 to 2.5 $\text{m}\Omega\text{cm}$. The laser-induced pyrolytic deposition of silicon on SOS was analyzed using numerical simulations of the temperature distribution caused by a focused laser beam. Comparisons were made between experimental and calculated cross-sections of deposited stripes. The measurements of piezoresistivity were carried out by controlled bending of samples of rectangular shape upon which the stripes had been deposited. The stripes deposited along various directions on the substrate revealed anisotropic behaviour in their piezoresistivity properties. The results show that the stripes tend to adopt the same epitaxial crystalline orientation as the SOS layer. The longitudinal gauge factor along the [110] direction of silicon, which direction is normally used in strain sensor applications, varied between 15 and 44 depending on the laser power applied. A local temperature near the melting point of silicon seems to be needed to assure the epitaxial growth.

1. INTRODUCTION

The laser-induced CVD of silicon stripes from silane with scanning laser beam has been the subject of many studies since the end of the seventies [see reference 1 and references therein]. The main technological interest has been in direct writing of doped silicon tracks as conductors in laser programmable integrated circuits such as gate arrays. Another possible field where the flexibility of the laser writing of stripes of various materials may find applications is sensor technology.

The piezoresistivity properties of silicon stripes deposited with a focused laser beam to examine their possible use as piezoresistive sensor elements has been studied. In an earlier report², some preliminary results of the piezoresistivity of silicon stripes deposited on sapphire were presented. As the piezoresistivity in a semiconductor is a highly anisotropic property, the applications would preferably require stripes having single crystalline structure with controlled orientation on an insulating substrate. The stripes deposited directly on sapphire, however, had a polycrystalline structure. Furthermore, the nucleation in the deposition process was difficult due to the very small initial absorption of the visible laser radiation in sapphire. In silicon-on-sapphire (SOS) layered structures, the thin silicon layer considerably increased the absorption of the laser radiation which made the laser-induced deposition easier and more regular than in the case of pure sapphire. The deposition of silicon stripes on SOS substrates with argon-ion laser and analysis of their piezoresistivity properties have been studied here.

2. LCVD OF SILICON ON SOS

A computer controlled laser facility with a 6 W argon-ion laser and two stepping motors for moving the focused laser beam were used to deposit doped silicon stripes on SOS substrates. A gas mixture of 99 % SiH_4 and 1 % B_2H_6 at a total pressure of 100 mbar was used as a reactant gas in a reactor chamber (static system). The beam of multi-line radiation of the argon-ion laser, the main lines of which were 488 and 514 nm or single line radiation at 514 nm, was focused on the substrate using an objective lens with a focal length of either 16 or 20 mm. The theoretical values of the spot diameter of the focused beam (1/e value assuming a Gaussian intensity distribution) were 5.0 and 6.2 μm for the two objectives, respectively. In practice, due to deviations from the Gaussian intensity profile and inaccuracy in determination of the focus depth, the spot diameter of the focus may have varied from 5 μm to about 10 μm . In careful experiments made in vacuum, it was found that for a TEM₀₀ beam at 514 nm, a power of 550 mW was needed to cause melting of the silicon layer of SOS. This was about a half of the power needed to reach the melting point on a bare silicon sample.

The stripes were deposited on plates cut from a SOS wafer, a sapphire crystal of (1102) orientation covered with an epitaxial 1 μm thick (100) type silicon layer. A scanning speed of 50 $\mu\text{m/s}$ was used in the experiments. Using the multi-mode radiation of the laser, a power of 0.55 to 1.0 W was needed for deposition. The dimensions, as well as the morphology of the deposited stripes, depended strongly on the power applied. At the lower limit of the power range, narrow stripes with approximately Gaussian cross-section were obtained, whereas for

increasing power, the top of the stripe first became flat, and with still increasing power the stripes became a volcano-like shape with a dip at the centre line. Irregularities due to the $2\text{ }\mu\text{m}$ steps of the stepping motor and ripples perpendicular to the polarisation of the laser radiation could be seen in most of the stripes. The width of the stripes varied between 2 and $8\text{ }\mu\text{m}$ and the thickness between 0.2 and $1.5\text{ }\mu\text{m}$. Top views of some stripes are seen in the SEM micrographs of Fig. 1, whereas some cross-sections of intentionally broken stripes are given in Fig. 2. The measured resistivity of the stripes was in the range 0.5 to $2.5\text{ m}\Omega\text{cm}$.

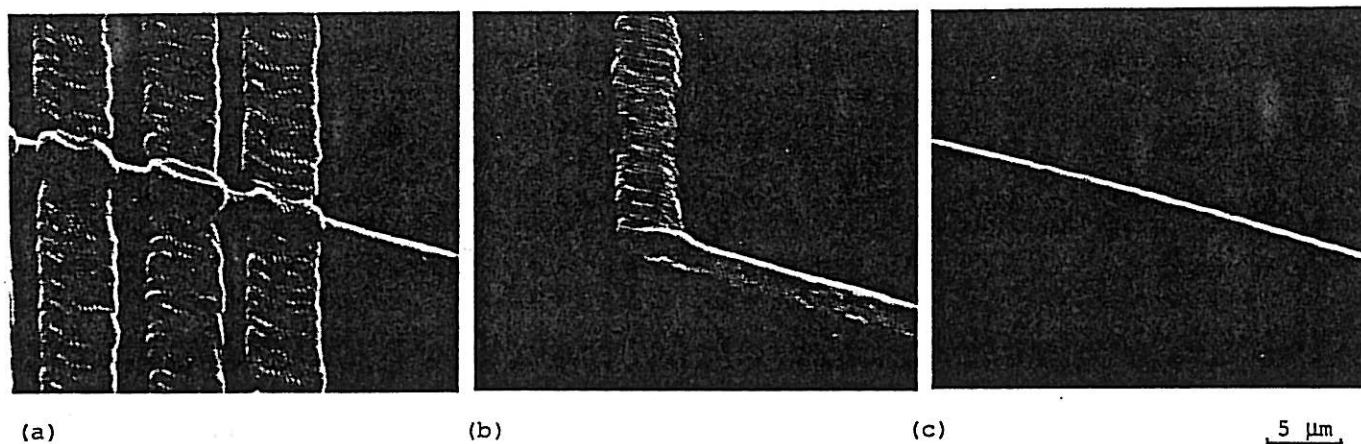


Figure 1. SEM micrograph of silicon stripes deposited on SOS with an argon-ion laser. The vertical stripes in part (a) have been deposited using a laser power of 0.8 W of visible multi-line radiation. The other stripes were deposited with a power of 0.55 W . The focal length of the objective lens was 16 mm .

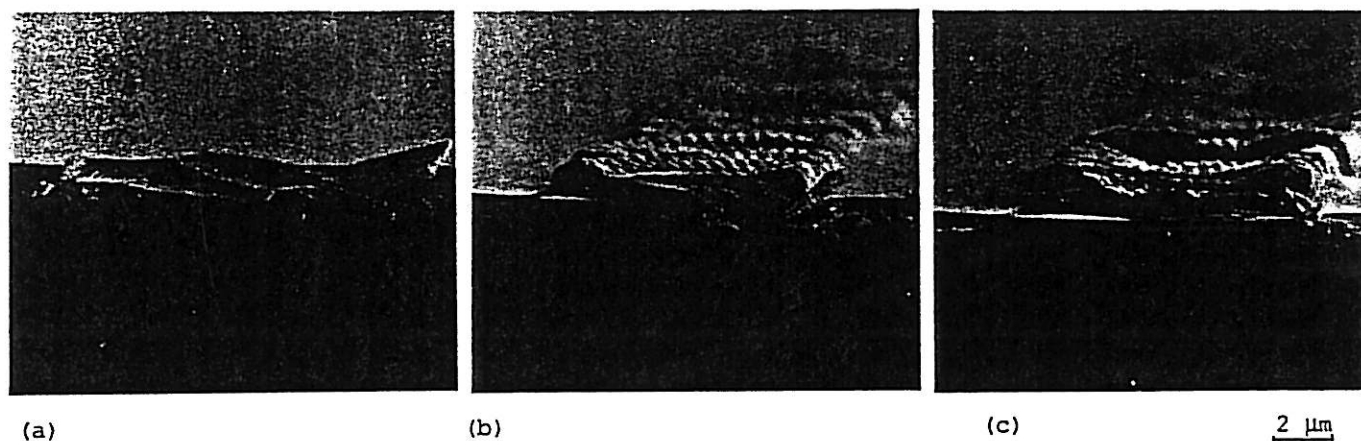


Figure 2. SEM micrographs of cross-sections of intentionally broken silicon stripes on SOS. Focal length of the objective lens was 20 mm , scanning speed $50\text{ }\mu\text{m/s}$, wavelength 514 nm , and the power 0.62 W in part (a), 0.78 W in part (b) and 1.01 W in part (c).

3. COMPARISON WITH NUMERICAL SIMULATIONS

Theoretical estimates for the stripe growth rate and the cross-section were also done. These are based on the temperature distributions obtained by similar numerical simulations as in the previous study³ and the consequent growth rate from the experiments⁴ and from the Arrhenius law with the activation energy $182\text{--}218\text{ kJ/mol}$.

The steady-state heat diffusion equation is numerically solved using the finite difference approach using temperature dependent material parameters. The step length of $0.5\text{ }\mu\text{m}$ for the relevant SOS substrate ($1\text{ }\mu\text{m}$ silicon on sapphire) under heating of the focused laser beam is applied and the surface temperature distribution is extrapolated from the topmost bulk values. The Gaussian beam width was adjusted to $8\text{ }\mu\text{m}$, in order to obtain such a temperature distribution that gives the measured maximum stripe thickness of $0.23\text{ }\mu\text{m}$ with the incident power 0.62 W and scanning speed $50\text{ }\mu\text{m/s}$.

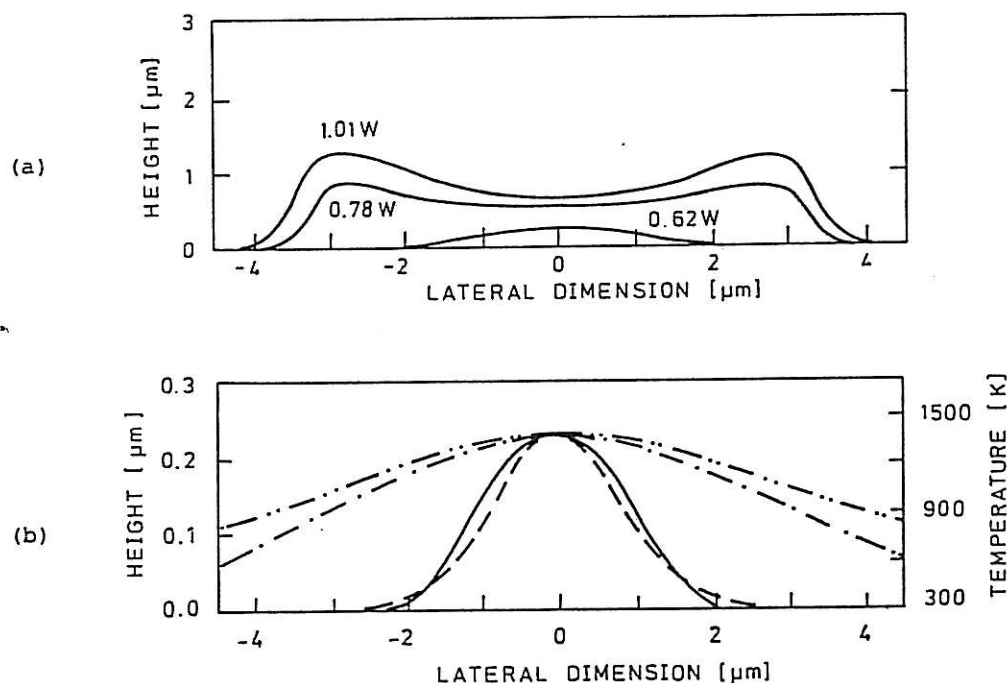


Figure 3. The cross-sections of doped silicon stripes deposited on SOS with different laser powers (a) and a comparison of measured thickness profile (—) for a laser power of 0.62 W with the simulated thickness profile (----) (b). The normalized profiles of the laser intensity (---) and temperature (.....) are also given in part (b).

The calculated growth rate and the resulting stripe cross-section shown in Fig. 3, appear to be nearly Gaussian, in accordance with the measurements. The $1/e$ widths of the simulated profiles using activation energies 182 and 218 kJ/mol were 2.6 and $2.4\text{ }\mu\text{m}$, respectively, which can be compared with the measured width of $2.6\text{ }\mu\text{m}$. It should be noticed that the temperature distribution is not Gaussian in shape and has somewhat larger width than the initial Gaussian laser beam intensity. The volcano-like structures obtained with higher power, need a more refined analysis because the deposition process itself has a strong influence on the temperature distribution and because of the complexity caused by melting.

4. PIEZORESISTIVITY MEASUREMENTS

The samples for the piezoresistivity measurements were rectangular slices of $7 \times 22 \times 0.43\text{ mm}^3$ cut from a $(1\bar{1}02)$ SOS wafer so that the main direction of the slice (the direction of the longest edges) was either $[2021]$ or $[\bar{1}101]$ of sapphire as shown in Fig. 4. These directions also correspond the $[110]$ and $[100]$ directions of the epitaxial silicon layer. Contact pads of $1 \times 1\text{ mm}^2$ were made by evaporation of copper through a metal mask prior to the laser writing of the resistors or by laser-induced CVD of doped silicon to the contact areas after deposition of the resistors of same material. Stripes of doped silicon were deposited between the contacts both parallel and perpendicular to the main direction of each slice. This allowed the measurements of both longitudinal and transversal piezoresistivity in one sample. A controlled strain up to 0.5×10^{-3} was accomplished by bending the slice with a micrometer, keeping the other end of the slice fixed. A more detailed description of the experimental method is given elsewhere⁵.

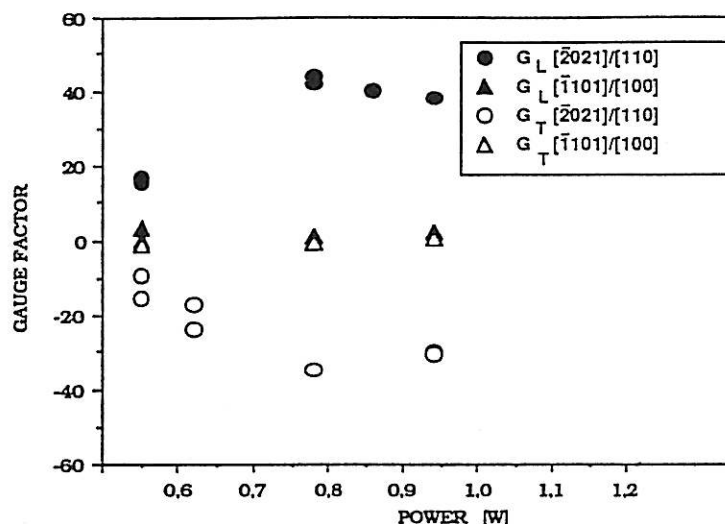


Figure 5. The measured gauge factors in doped silicon tracks deposited by laser-induced CVD on SOS substrates. The direction of strain is given with respect to the axes of both sapphire crystal and the epitaxial silicon.

The results given in Fig. 5 show a clear anisotropy in both longitudinal and transversal gauge factors of the deposited stripes. The maximum value of longitudinal gauge factor, $G_L = 44$, was obtained for a stripe along the $[2021]$ direction of sapphire. The transversal gauge factors for strain along this direction were only slightly smaller than the longitudinal gauge factors, but of opposite sign, as expected for epitaxial silicon having an $[110]$ direction along the $[2021]$ direction of the sapphire. The very small values of both longitudinal and transversal gauge factors for strain along the $[110]$ direction of sapphire are also in accordance with the expected epitaxial character of the silicon tracks. Fig. 5 also shows a dependence of the gauge factors on the laser power used in the laser-assisted deposition. At small powers, below 0.6 W, the gauge factors, even for most favourable orientation, are less than about 20. With increasing power, there seems to be a maximum in both longitudinal and transversal gauge factors at about 0.8 W.

5. DISCUSSION

The deposition of doped silicon stripes on SOS seems to be easily carried out using visible radiation of an argon-ion laser in a silane atmosphere. With the laser spot diameter of $5 \mu\text{m}$ ($1/e$ value), the width of the stripe might be below $2 \mu\text{m}$, presuming that the melting point of silicon is not exceeded. If the maximum spot temperature exceeds the melting point of silicon, the deposited stripe seems to become broader. Melting may also be behind the volcano-like profile with a dip at the centre line. According to the numerical simulations, the peak temperature is a steep function of both the incident laser power and the spot diameter. Because decreasing spot diameter results in increasing peak temperature, it is possible that the decreasing spot diameter through melting causes broadening of the deposited stripe. This is the case if the peak temperature initially is just below the melting point of silicon.

The morphology of the stripes does not differ essentially from that of the stripes deposited on silicon¹ or on silicon covered by thin oxide layer⁶. On the other hand, there is a great difference in the stripe morphology if deposited on the pure sapphire substrate². The low absorption of light in pure sapphire makes the nucleation much more difficult resulting in the irregular growth. The ripples perpendicular to the electric field vector of the laser radiation are clearly seen, at least in the stripes where the melting point of silicon has been exceeded during the deposition.

The resistivity of the deposited stripes between 0.5 to $2.5 \text{ m}\Omega\text{cm}$ corresponds to a boron concentration between $5 \times 10^{19} \text{ cm}^{-3}$ and $2 \times 10^{20} \text{ cm}^{-3}$, according to the curve of Irvin⁷. This value is considerably lower than the value of 10^{21} cm^{-3} obtained from the ratio of the concentrations of silane and diborane in the gas mixture. As calculated from the data of Tufte et al.⁸, the longitudinal gauge factor of silicon along the $[110]$ direction decreases from 75 to about 30 when boron content increases from 10^{19} cm^{-3} to 10^{21} cm^{-3} . According to this data, the value of $G_L = 44$ measured here would correspond to a boron content of $2 \times 10^{20} \text{ cm}^{-3}$, within the limits estimated above. Therefore, the concentration of charge carriers in the stripes seems to be only about 10% of the value implied by the mixing ratio.

The qualitative difference in the piezoresistivity of p-type and n-type silicon is reflected in their elastoresistivity coefficients m_{11} , m_{12} and m_{44} , or alternatively in the piezoresistivity coefficients π_{11} , π_{12} and π_{44} . In p-type silicon one of the three coefficients, m_{44} , is dominant, whereas in n-type silicon, $m_{44} \ll 2m_{12} \approx -m_{11}$. The equations for both longitudinal and transversal gauge factors along some crystal directions in a single crystal, as well as the average values corresponding to a polycrystalline material, are given in table 1 in terms of the m_{ij} coefficients. According to these equations, a resistor along [110] direction in a p-type epitaxial (100) silicon layer would have a large longitudinal gauge factor $\approx m_{44}$ and a transversal gauge factor of approximately equal magnitude but of opposite sign. Along an [100] direction, very small gauge factors are expected both for the longitudinal and transversal piezoresistivity. If, however, the resistor would be polycrystalline with roughly random distribution in the orientation of crystallites, there should not be any pronounced anisotropy in gauge factors with respect to its alignment on the substrate crystal.

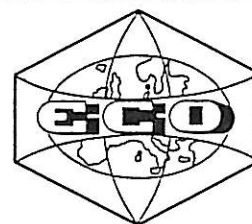
The anisotropy in the gauge factors is strong evidence towards the epitaxial structure of the stripes. The epitaxial character of the stripes seems to be most pronounced when laser powers above 0.75 W are used for deposition. At the lower limit of the applied laser power, the magnitudes of both G_L and G_T for strain along [201] direction of sapphire are considerable smaller than at 0.78 W. This may be due to crystallites having other than epitaxial orientation. The gauge factors for strain along the [1101] direction are, however, also in this case, very small, indicating a clear tendency towards epitaxial orientation. The results seem to confirm that a temperature near the melting point of silicon is needed to assure epitaxial deposition of silicon stripes on SOS. This is in agreement with the studies of Bäuerle¹, according to which the single crystalline growth would dominate over the polycrystalline growth at temperatures above a critical temperature $T = 1550$ K.

6. ACKNOWLEDGEMENTS

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