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To cite this version:

HAL Id: jpa-00219923
https://hal.archives-ouvertes.fr/jpa-00219923
Submitted on 1 Jan 1980

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CO₂-LASER ANNEALING OF BURIED LAYERS PRODUCED BY MEV ION IMPLANTATION

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Abstract.- Buried layers were obtained by implanting 3 MeV As⁺⁺-ions into Si-wafers. Annealing of these layers can be achieved with Q-switched CO₂-laser irradiation, but not with Q-switches Nd-YAG- or ruby lasers. It is shown that laser annealing shifts the doping profile towards the surface.

1. Introduction.- For many electronic devices it is necessary to fabricate doped and structured thin layers deep inside the bulk, so-called buried layers. Conventionally these layers are produced by covering the layer that is to be buried with epitaxial silicon. However, the technology for growing good quality epi-layers is rather complex and high energy ion implantation in the MeV range may become an efficient method to produce devices which contain buried layers.

During the processing of very large scale integrated (VLSI) devices, redistribution of the concentration profile has to be avoided. Therefore, the use of conventional high temperature processes to anneal radiation damage and to activate electrically the dopants is very limited and laser annealing of ion implanted layers may well be an answer to these problems. As it is known from many experiments with a ruby or Nd-YAG laser only about 0.5 µm deep implants can be annealed. The main question to be answered in our case, therefore, can be stated as follows: Is there a laser radiation appropriate wavelength, that penetrates deep enough and with sufficient intensity to anneal MeV implants?

2. Experiments.- Specimens were prepared by implanting As⁺⁺ ions at 3 MeV into <111> 100 nm n-Si wafers with a dose of 4.3 ×10¹¹ cm⁻², i.e. well below the dose needed for amorphization. The implanted wafers were either annealed in normal ambient air by irradiation with a light pulse emitted from a CO₂-laser (10.6 µm, P20 line) or for comparison by conventional thermal treatment at 730°C in N₂ for 15 minutes. In figure 1 the set up for laser annealing is shown schematically. At the exit of the laser the laser beam has a diameter of approximately 5 cm. The energy density on the wafer is controlled by the distance from the lens. The transmitted light is monitored by a photon-drag-detector. At the high light intensities involved (total laser out-put energy 15-20 J in 100 ns), the effect of an air break-through can be observed. The air break-through either occurs directly in front of the wafer or at the point, where the reflected light from the wafer surface is focussed.

At comparatively low energy densities, about one half of the laser light is transmitted through the wafer into the monitor (ca. 6 J out of 14 J). By increasing the energy density a critical energy density can be determined, at which the Si-wafer becomes almost non-transparent (transmitted energy ca. 1 J). However, it was found, that only at energy densities above this threshold an observable annealing occurs.
At present, we cannot prove, whether the decreased transmission is due to reflection from a molten surface layer of from a plasma sheet in the wafer or due to increased absorption.

The actual annealing experiments were performed at energies just a little under the breaking limit of the wafers (about 10 J/cm²).

The energy of the laser is mainly absorbed by free carriers. The light emitted from the plasma of the air breakthrough in front of the wafer impinges on to the sample to be annealed, increasing electron density in the conduction band and hence the free carrier absorption.

After depositing Schottky-contacts, the electrically active part of the profile was determined by a C(V)-measurement. In all cases good diode characteristics were found. At 10 V the thermally annealed diodes had a reverse current of 10 μA/cm² and the laser annealed samples values between 10 μA/cm² and 1 mA/cm².

In figure 2 the result of the laser annealing is shown. All results can best be compared with the purely thermally annealed samples (curve a), which corresponds to an approximately 100 % electrical activity of the implanted ions. The values of the mean projected range Rp and straggling ΔRp agree exactly with Smith's calculation (/1/, theory: 1.63 ± 0.30 μm, experiment: 1.63 ± 0.33 μm). Also the background doping level of 6 x 10¹⁴ cm⁻² corresponds to the manufacturer's data.

After the laser shot (curve b) about 50 % of the dopants show up. The doping profile shows considerable broadening. With an additional tempering step (770°C in N₂) almost all dopants become electrically active (̂=80 %, curve c). However, the doping profile is narrower than it was after the laser shot. Furthermore, the curve is shifted to smaller depth in respect to the thermal reference sample.

These experimental results can be explained by the following assumptions:

1) The migration of As (= shift of the doping profile) is only possible, if enough vacancies are present in the vicinity of the implanted As.
2) After the laser shot the implanted As is in a state where it forms a deep level, for instance as an As-vacancy complex.

The annealing process in this model proceeds as follows: During the implantation radiation damage is created a little bit closer to the surface than the implanted ions /2/. During thermal annealing the ions anneal in situ (curve a). During laser annealing As ions migrate to the region where the maximum vacancy concentration exists i.e. closer to the surface and form vacancy complexes.

The vacancy complexes give rise to deep electronic levels in the band gap. In the C(V)-measurement these deep levels appear as an apparent doping peak at a greater depth compared to their real location (curve b). During the thermal anneal the As-vacancy complexes are dissolved and the As dopants (now occupying shallow levels) show up in the place they have moved to during laser anneal (curve c).

This model was confirmed by a second set of experiments. In this case the wafers after implantation were first tempered at 440°C in N₂. By this treatment the number of vacancies is drastically reduced, without activating the implanted As. These wafers then were exposed to a CO₂-laser
shot (curve a in Fig. 3). After the laser shot some wafers were thermally annealed (curve b in Fig. 3). The explanation of the results follows the same lines as above, the only difference being, that in this case no vacancy concentration gradient towards the surface exists and thus the As has no tendency to move towards the surface during the laser shot. Again, the apparent shift of the concentration maximum of curve a to greater depth is attributed to deep levels. That the As, however, has not moved at all is shown by curve b, measured after an additional thermal anneal and corresponding exactly to curve a of figure 2, representing the profile of a purely thermally annealed sample.

3. Summary.- It is shown, that by irradiating a non amorphous deep As-implant in Si with a pulse from a CO₂-laser deep levels in form of vacancy-As complexes are created. During the laser shot the As concentration moves in the direction of the vacancy concentration gradient.

Acknowledgments.- The authors wish to thank K. Bethge and H. Baumann for helpful assistance in performing the As-implantation at the high energy implanter of the Institut für Kernphysik (Universität Frankfurt). Furthermore thanks are due to F. Schroeder and W. Fuss for the laser shots performed at the MPI für Plasmaphysik, Garching.

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