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Luminescence in slipped and dislocation-free laser-annealed silicon

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Photoluminescence of cw laser-annealed silicon shows a dramatic difference in electronic behavior of the reconstructed material depending upon either creation or suppression of dislocations. Beyond a critical exposure time slip appears, and the luminescence of these samples is dominated by dislocation-related defect levels.

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Laser annealing of imperfect semiconductors has attracted much attention[1–5] as a novel method of improving and controlling structural and electronic properties of semiconductor materials. Ion-implantation-induced damage can be removed, or amorphous material can be restructured by short-pulse or cw illumination with lasers. The detailed physical properties of such treated materials, however, depend strongly on the annealing process and have, as far as optimal degree of perfection is concerned, not been completely determined.

This letter reports on photoluminescence studies of cw laser-annealed Si and demonstrates the drastic influence of dislocations generated under specific annealing conditions. Exact control of the laser power and the illumination time is shown to be of great importance for the properties of the annealed material.

It has previously been shown that epitaxial regrowth of disordered silicon layers formed by ion implantation can lead to the formation of slip dislocations.[6,7] These dislocations are likely to affect the electron-hole recombination. The recombination in turn can be probed very sensitively in photoluminescence experiments.[8] Therefore this method of analysis is used here to investigate the different electronic behavior of Si depending on the presence or absence of dislocations.

Silicon wafers were used which had been amorphized by implantation of As, P, or B at 100 or 180 keV with doses of 1×10^{15}–3×10^{16} atoms/cm^2 on $\langle 100\rangle$ and $\langle 111\rangle$ surfaces. The implanted samples were annealed by irradiation with a 15-W cw Ar ion laser in the TEM_{00} mode. The exposure time was adjusted by means of an electromechanical shutter or by scanning the wafers with a computer-controlled xy table with 5-μm step resolution. The laser intensity was adjusted and controlled by regulation of the excitation current. The degree of lattice perfection was analyzed by x-ray topography, optical micrography, and preferential etching techniques as previously described.[6,7]

Figure 1 gives an example of optical micrographs taken from slipped as well as from nonslipped single-shot exposures. Comparison of the annealing parameters (see figure caption) reveals that a change in exposure time of only about 15% leads to a transition from nonslipped to slipped silicon. In addition, a change in power density of about 20% (from 7 to 8.5 W) causes a transition from solid phase epitaxial (SPE) to liquid phase epitaxial growth (LPE).[9] These annealing procedures thus constitute a highly controlled method of preparing samples with or without dislocations, but otherwise largely identical in structure, chemical composition, and thermal history. Comparatively small variations of the anneal conditions can thus result in different crystalline perfection with severe consequences for the electronic properties.

Figure 2 shows the luminescence spectra of two large-area annealed samples. Anneal conditions are identical to those in Fig. 1. Photoluminescence is excited with 514-nm

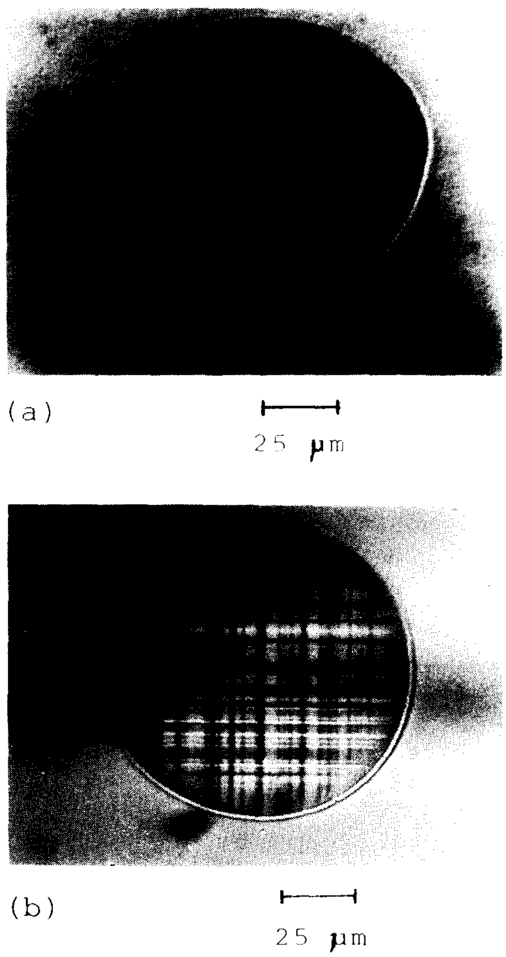

FIG. 1. Solid phase epitaxial regrowth shown in differential interference contrast: (a) laser exposure at 6 W, 30 ms, no slip dislocations; (b) 7 W, 100 ms, cross grid of slip lines reveals dislocations.

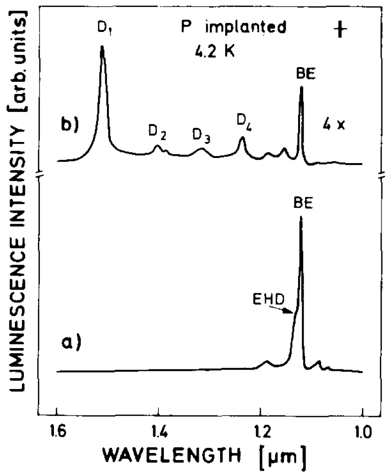

FIG. 2. Photoluminescence spectra of P-implanted laser-annealed Si. Large-area annealing with identical regrowth mode is in Fig. 1. (a) Without dislocations. (b) With dislocations; intensity enlarged fourfold relative to (a).

Ar laser light, and recorded with a grating monochromator (Jobin Yvon H 25) and a selected cooled Ge diode detector (North Coast EO-817L). The dislocation-free sample exhibits the well-known emission lines of bound-exciton (BE) and electron-hole drops (EHD's). The presence of EHD luminescence indicates relatively long carrier lifetimes. The sample containing dislocations (estimated density about 10^8 dislocations/cm^2), on the other hand, shows no EHD emission; instead four new intense and broad lines are seen and marked D1–D4 in Fig. 2(b). These lines were formerly found by Drosdov *et al.* [10,11] in plastically deformed bent silicon crystals and have been attributed to dislocations. The exact energetic positions and the relative intensities of these four lines are sample dependent. Usually, our samples show lines D1 and D4 as most intense and also exhibit a fine structure different from Ref. 11. Further details, including studies of the influence of temperature, excitation intensity, and dislocation density will be published elsewhere.[12] No dependence on the chemical nature of the dopant is found: As, P, and B reveal no significant difference in the D lines, but of course show their respective characteristic bound excitons. We also see no influence of the crystal orientation.

Although the atomic structure of the recombination centers is as yet not clarified, our experiments confirm the previous assignment [10,11] of the D lines as being caused by the presence of dislocations. Other authors have also reported photoluminescence of laser-annealed silcon.[13] Their spectra generally show a multitude of broad bands which we cannot detect in our SPE regrown material. Our LPE material, [6,7] however, also shows rather broad and structureless spectra.

We believe that our results are significant in two respects. First, anneal conditions have to be properly chosen and controlled in order to achieve the dislocation-free SPE-regrown, rather than the dislocated, lattice. Only under these conditions can one obtain well-defined electronic behavior resembling that of perfect single-crystal bulk silicon. Secondly, cw laser annealing provides an extremely well controlled means of generating dislocations in silicon for further detailed studies of this type of defect.

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