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Growth, Characterization and Device Fabrication of Boron Delta Doped Structures by Si-MBE

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Boron incorporation in delta-doped layers in Si(100) thin films grown by MBE has been investigated by a combination of *in-situ* and *ex-situ* analysis techniques. Layer width of three (200) atomic planes was measured by high resolution transmission electron microscopy even for coverages close to 1 monolayer. Delta doped based diodes are also demonstrated.

1. INTRODUCTION

The production of extremely thin, fully-activated and defect-free, selectively doped layers (delta doping) has recently attracted intense research due to the possibility of artificially creating low-dimensional structures and very localized, heavily doped areas in a semiconductor. In the present paper we report on the growth, *in-situ* and *ex-situ* characterization and device production of boron delta-doping based structures by silicon molecular beam epitaxy (MBE). The first delta-layer based diodes exhibiting negative differential resistance (NDR) in the electron vertical transport at room temperature are also presented.

2. GROWTH, ANALYSIS METHODS AND DEVICE FABRICATION

Boron δ-doped structures were grown on Si(100) substrates by MBE, using a modified VG-V80 UHV system. A high-temperature elemental B source with fluxes up to $5x10^{13}$ $cm^{-2}s^{-1}$ was used to obtain different planar doping levels.

In-situ characterization was performed by reflection high-energy electron diffraction (RHEED), low-energy electron diffraction (LEED) and Auger electron spectroscopy (AES) in a set of capping experiments of δ-doped structures. Si was overgrown on top of different coverages of B layers at different substrate temperatures (450-650°C). At different steps of the capping, the growth was interrupted, the sample cooled down to room temperature and *in-situ* AES and LEED measurements were performed. By this way, the gradual dopant segregation mechanism can be accessed and quantified, and a complete surface characterization can be done.

The information provided in these experiments regarding the best temperature to minimize the δ-layer broadening was applied in the growth of single and multi-delta doped layer structures at low temperatures (≤ 500°C) for *ex-situ* structural characterization. The coverage of each δ-layer in this case was established by AES calibrated data combined with secondary ion mass spectrometry (SIMS) characterization of homogeneously doped layers with the same fluxes and growth temperatures. Cross-sectional transmission electron microscopy (XTEM) including high-resolution TEM (HREM) was performed to investigate crystal quality, δ-layer width and possible presence of precipitates and defects. Samples for XTEM analysis were prepared by Ar ion thinning. Observations of the specimens were carried out using a Philips CM20 UT microscope operated at 200 kV. Dark field imaging with the diffracting vector **g** = [400] was used in order to enhance strain contrast at δ-doped layers.[5] HREM images were obtained close to Scherzer focus.

Finally, the utilization of delta doping in novel device structures was demonstrated by fabricating diode structures consisting essentially of two B δ-doped layers (with coverages of 1×10^{13} cm^{-2}, each) separated by 140 Å and placed between two n^+ electrodes. Low temperatures (≤ 500°C) were used for growth and device processing (reactive plasma etching and passivation via plasma enhanced chemical vapor deposition). Current-voltage (I-V) characteristics were acquired at room temperature and at 77 K, via a microprocessor-controlled curve-tracer parameter analyser with the probes connected to ohmic Au-Sb alloy contacts on the sample.

3.RESULTS AND DISCUSSION

The temperature dependence of B incorporation for Si overgrowth on δ-doped layers was investigated by capping experiments and the results are displayed in Fig. 1 for two different substrate temperatures (T_S). The

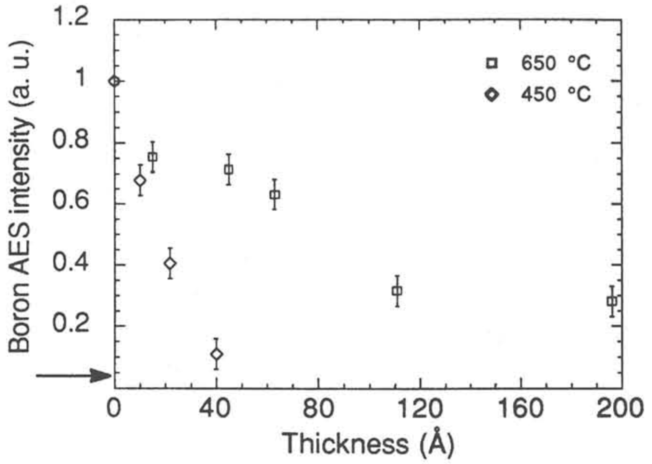

Figure 1: Boron Auger 179 eV electron transition intensity (normalized to the initial coverage) as a function of Si capping thickness at substrate temperatures of 450 and 650 °C. The arrow indicates approximately the detection limit of the technique.

initial B coverage was ~ 0.10 ML (1 ML = 6.8×10^{14} cm^{-2} for Si(100)) and the growth rate was 0.2 $Ås^{-1}$. The B incorporation is stronger in the low temperature case, 450 °C, and the long tail in the 650°C curve indicates a significant broadening which detrimentally reduces the sharpness of the structure. In this experiments, B signal can be observed up to at least 200 Å from the original doping position, with an intensity well above the AES detection limit.

The difference in the B incorporation at the two temperatures can be quantified by assuming that the amount of incorporated dopant is proportional to the dopant adlayer density, n, what is true for low-desorption adatoms[1], such as B in Si. In this case, n decays exponentially with $-x/\Delta$. Here Δ is the decay length, a measure of the δ-layer broadening, and, in the B case, it equals the dopant segregation ratio (i.e., the ratio between the surface and the bulk dopant concentrations). x is the capping thickness. From Fig. 1, Δ is 120 Å for growth at 650 °C, but only 18 Å for the similar structure at 450 °C. The increase in Δ with T_S, and thus in the segregation ratio, by almost an order of magnitude, is consistent with SIMS measurements of B incorporation in similar structures.[1] The abrupt reduction in the B incorporation close to 650 °C is attributed to a transition between a low-temperature kinetically-limited regime to a high-temperature equilibrium regime. The incorporation above 650 °C is known to increase slowly,[1,2] but it is still low.

A linear extrapolation of the data in Fig. 1 for the initial decay stages, provides, according to a zeroth-order incorporation formalism, an estimate of the effective solubility constant, K, at each temperature. In this case, a value of 4×10^{19} cm^{-3} for the solid solubility of B in Si at 650 °C can be estimated. The first stages of capping at such temperature range is also characterized by significant surface roughening as evidenced by a diffuse Si(2x1) pattern in LEED and RHEED. Electrical measurements in homogeneously, heavily B doped samples grown at this temperature have shown that 6×10^{19} cm^{-3} is the maximum carrier

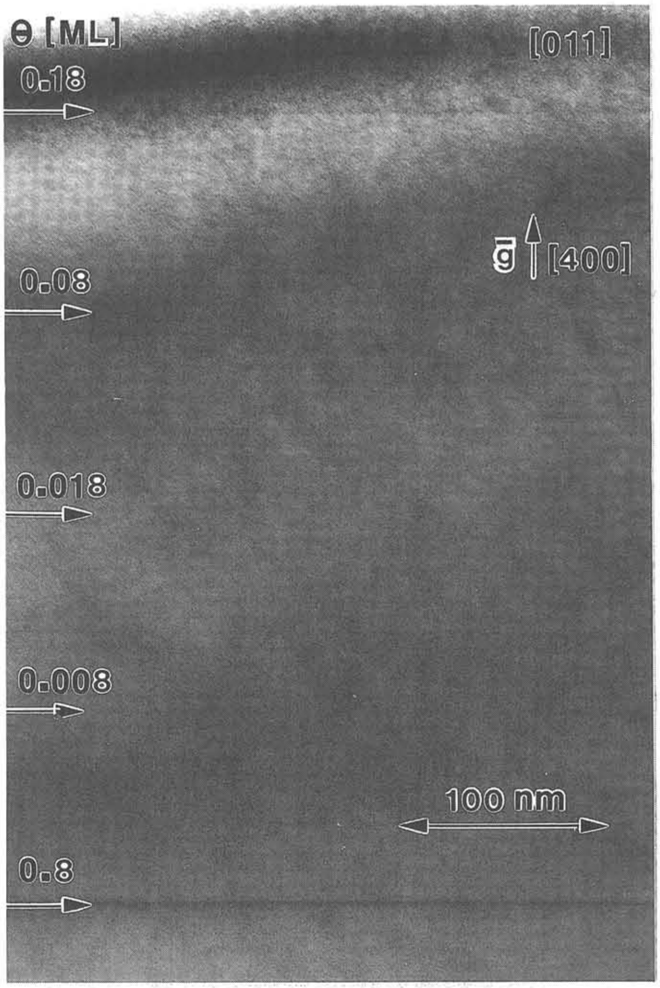

Fig. 2. Dark-field, **g** = [400], cross-sectional TEM image from the [011] zone axis of a MBE-deposited Si film on Si(100) with modulated B δ-doped layers with nominal coverages Θ = 0.8, 0.08, 0.018, 0.08, and 0.18 monolayers (ML, indicated by arrows). The growth temperature was 500 °C and the growth rate was 0.72 $Ås^{-1}$.

concentration fully activated,[3] i.e., the maximum amount which can be incorporated substitutionally, in agreement with our estimate of K.

The structural characterization was performed in more detail by medium- and high-resolution TEM. Figure 2 shows a dark-field XTEM image from the [011] zone axis of a MBE-deposited Si film grown at 500°C with a Si rate of 0.72 $Ås^{-1}$ with modulated B δ-doped layers with nominal coverages Θ = 0.8, 0.008, 0.018, 0.08, and 0.18 monolayers. The first layer is ~100 nm from the film/substrate interface. Selected area electron diffraction showed that the layers were epitaxial with no threading dislocations. Contrast from the 0.18 and 0.8 ML δ-doped layers can be seen in Fig.2, but weak contrast was observed in the microscope also from the 0.08 ML layer. The 0.8 ML layer was continuous and no precipitation was observed as corroborated also by HREM.

Figure 3 shows an HREM image of the B δ-doped layer with Θ = 0.8 ML. The layer showed contrast due to either compositional difference to Si or lattice strain over an average thickness of three (200) planes ≈ 8 Å. This narrow width is consistent with the AES data from

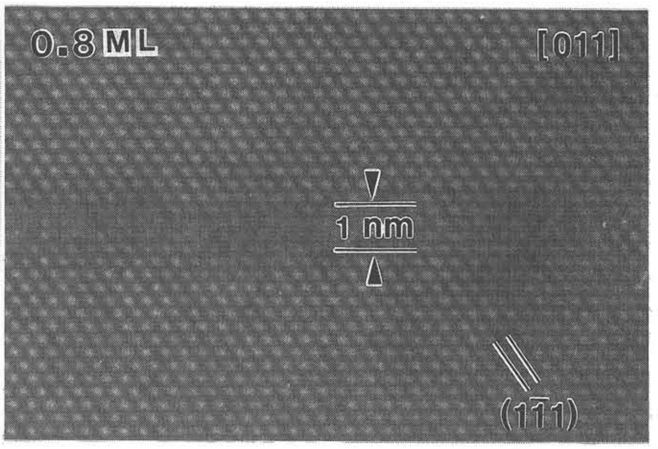

Fig. 3. High-resolution cross-sectional TEM image from the [011] zone axis of a MBE-deposited Si film on Si(100) with a B δ–doped layer with nominal coverage Θ = 0.8 ML. The growth temperature was 500 °C and the growth rate was 0.72 Ås^{-1}.

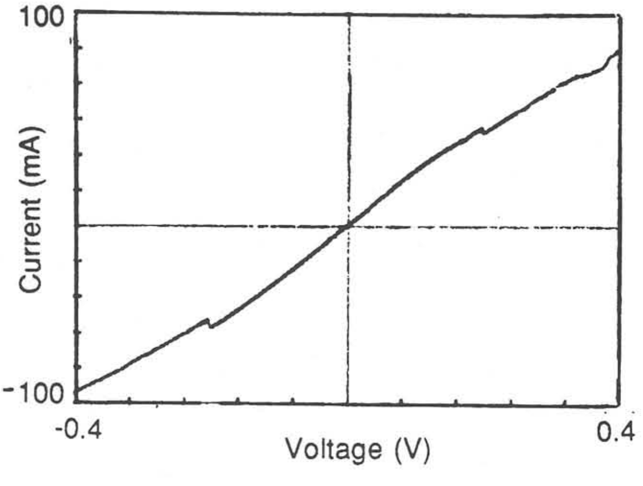

Figure 4: I-V characteristics of a delta-doping based diode measured at room temperature.

Fig. 1, which gives a decay length of 18 Å, but for a much lower growth rate, despite T_s was also 50 °C lower. The Si{111} planes were continuous across the B layer, i.e. no strain relaxation or precipitation had occurred.

The sharpness and excellent material quality of B δ-layers as demonstrated above were utilised in diode structures where two δ-layers created potential barriers in the electron vertical transport between a n^+ substrate collector and a top n^+ emitter layer. The barrier heights correspond to 0.02 ML coverage, 140 Å apart from each other. Measurements at 77 K and at room temperature (Fig. 4) showed clear negative differential resistance (NDR) effects obtained around 0.192 V bias, indicating a tunneling process involving the δ-doped barriers. The shape of the NDR is clearly N type, where the devices jump from on to off state for increasing voltage. The structure is symmetrical and at room temperature a peak-to-valley ratio (PVR) of 1.1 was obtained. No derivative measurements of the I-V curve were needed to identify the effect, but other small features may be present. The results suggest that tunneling can occur via a resonant mechanism, where the applied bias aligns the Fermi level to a bound state inside the well system created by the two δ-layers.[4] This possibility depends of course on the details of the energy levels created by the overlapping potential of the two δ's. To access this information a self-consistent calculation is required. A preliminary estimate on basis of the solution of Poisson's equation for this system suggests that the barriers can be very high and may even reach the conduction band edge. In this case, an interband tunneling could be favored by the sharp δ structures. Despite the modest PVR obtained in the measurement, the structure is very promising for future optimization work, and the fact that clear NDR can be observed at room temperature is remarkable.

4. CONCLUSION

Boron delta doping in Si-MBE has been characterized by *in situ* and *ex-situ* analysis methods. The temperature dependence of the layer broadening and different B incorporation regimes were determined from *in-situ* measurements. Electron microscopy confirmed that very thin, precipitation-free planar doped layers can be obtained even at coverages near 1 monolayer. Finally the utilization of δ-layers in novel devices with NDR effects was demonstrated.

5. ACKNOWLEDGEMENTS

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