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Article Title: p-type delta-doped layers in silicon: Structural and electronic properties
Year of publication: 1991
Link to published version: http://dx.doi.org/10.1063/1.104076
Publisher statement: none

p-type delta-doped layers in silicon: Structural and electronic properties

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(Received 12 February 1990; accepted for publication 26 July 1990)

We report on the properties of *p*-type delta-doped layers prepared in molecular beam epitaxial-Si by growth interruption and evaporation of elemental B. Secondary-ion mass spectrometry measurements at several primary ion energies have been used to show that the full width at half maximum is ~2 nm. Hall measurements confirm that the layers are completely activated at 300 K with a mobility of 30 ± 5 cm^2/V s for a carrier density of $(9 \pm 2) \times 10^{12}$ cm^{-2}. At temperatures below 70 K nonmetallic behaviour is observed which we have attributed to conduction between impurity states. It is concluded that the critical acceptor separation for the Mott metal-insulator transition in this system is significantly less than the value found in uniformly doped Si:B.

Delta-doped layers are expected to have novel electronic properties which should find numerous device applications[1,2] and the planar impurity distribution is well suited to the investigation of two-dimensional (2D) metal-insulator transitions.[3]

Delta doping has recently been achieved in molecular beam epitaxial (MBE) Si using Sb[1] or Ga[4] in combination with solid phase epitaxy (SPE) and Sb[5] or As[6] with low-energy implantation. Here we report on the characterization of B δ layers produced in MBE Si using growth interruption and evaporation of elemental B, as first reported by Mattey *et al.*[7]

Secondary-ion mass spectrometry (SIMS) was carried out in a quadrupole instrument (EVA 2000) using O_2^+ primary ions at normal incidence. Figure 1 shows a depth profile taken using extremely low-energy primary ions (450 eV/0^+). The areal dopant density is 1×10^{13} cm^{-2} and the full width at half maximum (FWHM) 3.6 nm. Also shown in Fig. 1 is the reconstructed profile at zero impact energy which has FWHM 2.7 nm and which has been obtained as follows: A series of SIMS profiles was taken through the delta layer with primary ion energy *Ep* in the range 450 eV/0^+ to 1.7 keV/0^+ and showed two expected effects: (i) Increasing asymmetry and broadening of the delta profile due to atomic mixing and beam incorporation. (ii) An apparent shift of the delta peak towards the surface with increasing energy (the differential shift[8]). Figure 2 shows the dependence of the leading and trailing slopes, FWHM, peak concentration, and position on *Ep*. If the broadening and shifting processes are all linearly dependent on energy, the data of Fig. 2 may be extrapolated to *Ep* = 0 giving the reconstructed profile shown in Fig. 1. It should be noted that this reconstruction constrains the profile shape to exponential up and down slopes meeting at a cusp. At present it is not possible to say how close this is to the true profile. It is likely that density renormalization effects,[9] not intrinsically dependent on *Ep*, give rise to residual broadening which makes the reconstruction a worst case. We have used an alternative method to show that this is so. A series of profiles of a 5 keV boron implant in Si was taken over the same energy range as the delta. Assuming that the decay slope on the δ profile was entirely limited by mixing and incorporation effects, the slope values at each energy were used to correct the decay slope of the implant profile and extract its true magnitude. This process was found to give an implant profile independent of *Ep*, showing that, even at 450 eV/0^+, the δ profile was entirely shaped by atomic mixing and beam incorporation effects. Therefore the true width of the δ layer is narrower than that obtained from the profile at *Ep* = 450 eV by an unknown amount, probably by at least a factor of 2, i.e., the

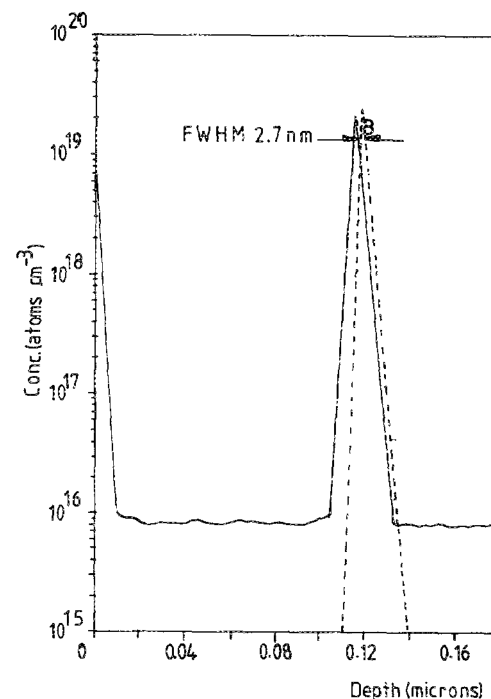

FIG. 1. SIMS profile of boron δ layer obtained using 450 eV 0 + ions at normal incidence (full line) and the reconstructed profile at zero impact energy (broken line).

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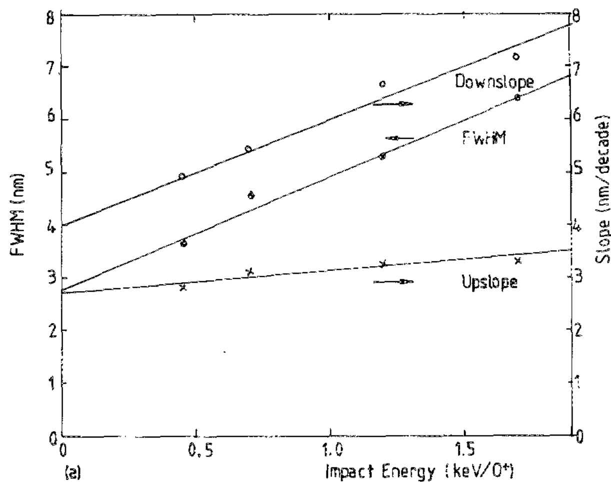

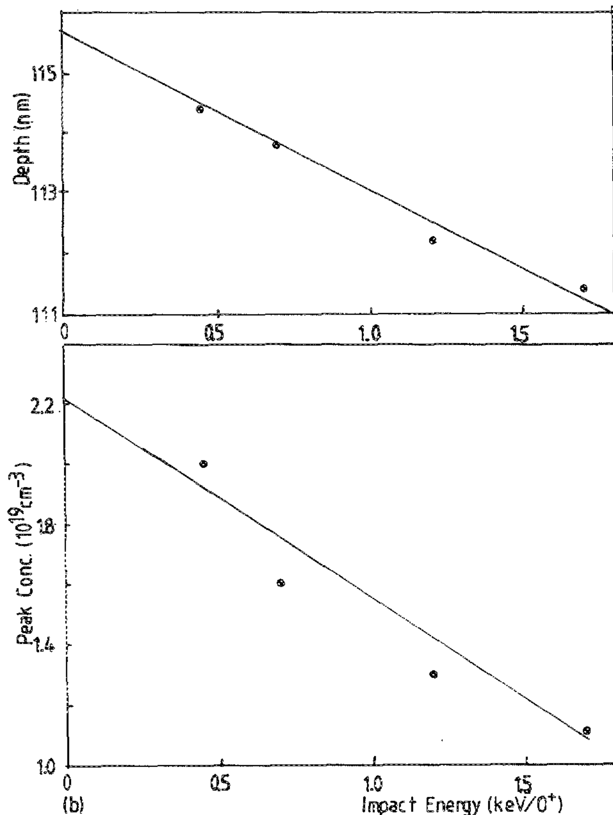

FIG. 2.(a) Dependence of FWHM, upslope, and downslope of SIMS profiles on primary ion energy. (b) Dependence of apparent depth and peak concentration of SIMS profiles on primary ion energy.

true width is ⩽2 nm. This is confirmed by transmission electron microscopy which indicates a layer width of approximately 2 nm.[7]

To study the transport properties of the layers Hall bars were fabricated[7] with a room-temperature plasma-grown oxide[10] for surface passivation.

At 300 K, Hall measurements on several samples from a delta layer of peak doping of concentration 2×10^{19} cm^{-3} and areal doping density 1×10^{13} cm^{-2}, as determined by SIMS, gave a sheet carrier density of $(9\pm2)\times10^{12}$ cm^{-2}. This suggests complete activation at 300 K but assumes a Hall scattering factor of unity and ignores the possible effects of quantum confinement. However, the sheet carrier density obtained from capacitance-voltage measurements confirms complete activation.[7]

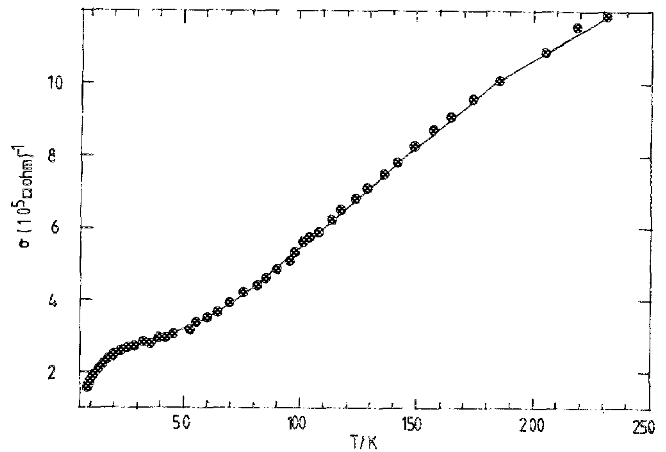

FIG. 3. Temperature dependence of the conductivity of a boron δ layer with sheet carrier density of 9×10 cm^{-2}. The solid line represents the best fit to the data.

The measured Hall mobility in the layer is 30 ± 5 $cm^2\,V^{-1}\,s^{-1}$, which is somewhat lower than the figure of 53 $cm^2\,V^{-1}\,s^{-1}$ (Ref. 11) obtained in uniformly doped Si:B of the same doping concentration (i.e., 2×10^{19} cm^{-3}).

The depressed mobility in the doping spike could, of course, be a consequence of the depletion layers at its edges. However such an effect is not observed in Sb δs in Si[15] and a more interesting possibility arises from the work of Bangert *et al.*,[12] who have shown that confinement lowers the energy of the ground-state heavy-hole subband with respect to that of the light holes. It is therefore possible that transport in this subband dominates, with a consequent increase in effective mass and in scattering.

Figure 3 shows the variation of the conductivity of this layer with temperature. Assuming the conductivity is due to a series of exponential terms with pre-exponential factors σ_i and activation energies ϵ_i, the data were fitted to

$$\sigma_T=\sum_i \sigma_i \exp -\frac{\epsilon_i}{kT} \tag{1}$$

where k is Boltzmann's constant. The resulting values of σ_i and ϵ_i are shown in Table I. At the highest temperatures the activation energy ϵ_1 is indicative of the excitation of holes into the valence band, from which we conclude that the Fermi energy lies in impurity states. For temperatures below ~70 K impurity conduction is dominant. The activation energy ϵ_2 is taken as evidence for transport in an

TABLE I. Pre-exponential factors and activitation energies obtained from fitting the data of Fig. 3 to Eq. (1).

i	$\sigma_i(10^5\ \Omega)^{-1}$	ϵ_i(meV)
1	23.1 ± 0.40	20 ± 0.3
2	1.80 ± 0.10	0.76 ± 0.02
3	1.79 ± 0.09	0.58 ± 0.03

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upper Hubbard (A^+) band while ϵ_3 is thought to be associated with nearest-neighbor hopping in the lower Hubbard (A) band. The observation of conduction in the A^+ band together with the low values of activation energy suggests that the impurity separation in this sample is close to, but above, the critical value for the metal-insulator transition.[13] This behavior is somewhat surprising. The onset of metallic behavior occurs at an average impurity separation of 3.5 nm for uniformly doped Si:B,[14] whereas the average impurity separation in the middle of the δ layer is 2.2 ± 0.1 nm, as deduced from the peak concentration of 2.2×10^{19} cm^{-3}. This discrepancy cannot be explained by broadening of the δ layers during Hall bar fabrication. Resolution-limited SIMS measurements (using 2.2 keV/ 0^+ primary ions) showed, to within experimental error, no change in the profile after annealing. Thus, we deduce that the layer is broadened to a maximum FWHM of $\simeq 5$ nm which implies an increase in the average impurity separation, assuming a Gaussian impurity profile, to $\simeq 2.9$ nm which is still significantly below the predicted critical value. Similar behavior has been observed in Sb[15] and As[6] δ layers in Si. In contrast the transition does occur at the predicted impurity separation for Si δ layers in GaAs.[16]

Theoretical work on the Mott transition[18,19] has shown that the critical separation R_c depends on carrier effective mass and on the number of valleys populated by the charge carriers. We are therefore investigating the possibility that the observed decrease in R_c in delta-doped Si:B is due to splitting of the valence-band degeneracy by carrier confinement, which is also suggested by the low value of the room-temperature Hall mobility.

It is pertinent to point out that the low value of R_c is not a simple consequence of the random distribution of impurities, this feature being common to both the uniformly and delta-doped samples. However we cannot rule out the possibility that depletion effects in the δ-doped samples could lead to Anderson localization[13] and the suppression of metallic behavior.

In conclusion, P-type delta-doped layers have been prepared by growth interruption and evaporation of elemental B. From SIMS analysis it is deduced that the layer FWHM is $\leqslant 2$ nm. Hall measurements suggest complete activation at 300 K for a sheet carrier density of $(9 \pm 2) \times 10^{12}$ cm^{-2} with a mobility of 30 ± 5 cm^2/V s. The low-temperature behavior of the resistivity is consistent with nonmetallic conduction in impurity states. An anomalously small value of the critical impurity separation for the Mott transition is observed, which is the subject of further studies.

The authors wish to thank R. F. Houghton (Warwick) for layer growth and A. Gundlach (Edinburgh) for processing the Hall bar structures.

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