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Shallow Sb-doped Si surface layers formed by recoil implantation

H. L. KWOK
Department of Electrical and Computer Engineering, University of Victoria, Victoria, British Columbia, V8W 2Y2, Canada

S. C. WONG
Department of Electronics, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong

Recoil implantation was used to form shallow n+ layers on p–Si by implanting 150 keV Ar^+ ions through evaporated Sb layers. By varying the Sb layer thickness, different dopant profiles were achieved. Based on the sheet resistance measurements, it was found that the dopant profiles deviated from theory when the Sb layer thickness was small. Damage effects related to energy deposition by the primary ions were used to explain the differences. It was suggested that these effects could significantly affect the dopant activity and the redistribution of the atoms during heat treatment. These effects were less important for those samples with thick Sb layers. For shallow p–n junction formation, it was essential to keep the damage effects to a low level.

1. Introduction

The achievement of a shallow and yet highly doped surface layer is of particular interest in the formation of shallow junctions. A lot of effort [1, 2] has been made to fabricate and characterize these highly doped surface layers and it is understood that the detailed properties may well be very complex [2]. For n+/p–Si junctions, As and Sb have often been chosen as the dopants since they are heavier atoms and would be less mobile when subjected to further heat treatment [3]. The requirement for a highly doped surface layer cannot be met by the conventional diffusion or ion implantation process because these profiles are normally Gaussian. Recoil implantation has been suggested as a solution to this problem [4]. Instead of the dopant being implanted directly as in the standard implantation process, recoil implantation makes use of the energy transfer from the primary ions to the dopant deposited as a thin film on the substrate. Through a proper combination of the ion beam energy and the dopant film thickness, an extremely steep and monotonically decreasing dopant profile could be achieved.

This work investigated the electronic properties of Sb-doped Si surface layers formed by recoil implantation. Ar^+ was the primary ion chosen since it does not directly interfere with the electronic properties. Because of the substantial energy transfer occurring in the recoil process, damage effects will be significant, depending on the energy deposition. These damage effects may usually be removed after heat treatment at a sufficiently high temperature. Recoil implantation has the advantage of forming a monotonically-decreasing dopant profile. This is highly desirable in the formation of very shallow junctions [3]. Furthermore, by a proper adjustment of the surface Sb layer thickness, it is possible, at least in principle, to adjust the junction depth to any arbitrary value.

Sheet resistance measurements were the main experimental tool. Simulated profiles were calculated based on the Boltzmann transport model [5]. Particular attention was paid to the damage effects, which were assumed to be primarily related to the energy deposition during collision. Such effects may result in lattice disruption (amorphisity), or may reduce transport parameters like mobility. Some very interesting observations were made in this work pointing to how damage effects could affect the dopant redistributions in addition to their effects on the electronic properties.

2. Experimental procedure

Wacher chemitronic ⟨1 0 0⟩-oriented p-type Si wafers were used in this work. The resistivity was 10 to 20 ohm cm^{-1} (the measured sheet resistance was ca. 360 ohm/square). These wafers were first cleaned using standard IC procedure prior to recoil implantation. Sb (purity: 99.99%) was deposited using an E-beam evaporator. The film thickness was varied from 60 to 175 nm. The values were monitored using a quartz oscillator and should be uniform within $\pm 10\%$. Ar^+ was the primary ion used and the energy was 150 keV. The implant dosage was $1 \times 10^{15}\,cm^{-2}$.

After recoil implantation, the Sb layers were removed using a mixed solution of $HNO_3 : HCl : H_2O$ (1 : 1 : 1). Isochronal annealing was carried out in a N_2 atmosphere for 20 min. The annealing temperature was 1100° C. This temperature was chosen since it has been reported [6] that below this temperature the stability of the Sb atoms was questionable. Sheet resistance measurements were made to monitor the

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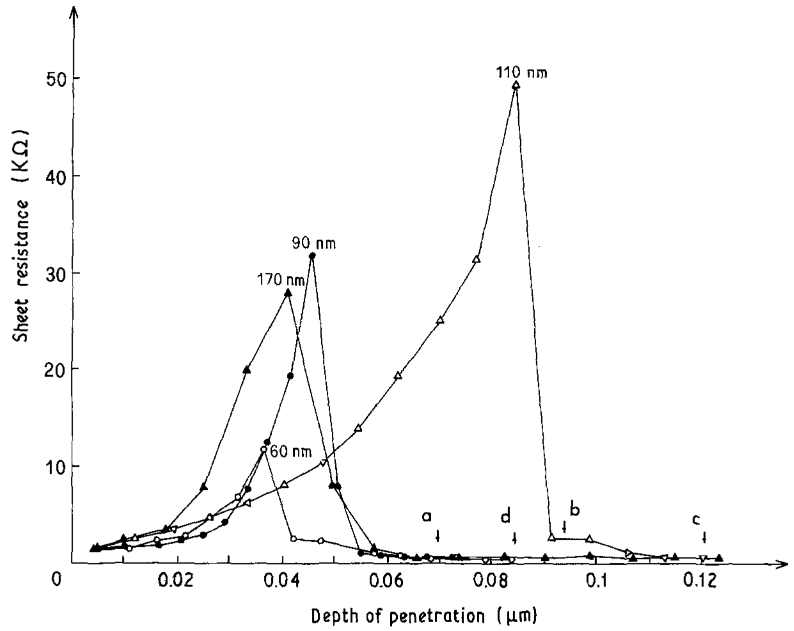

Figure 1 Sheet resistance profiles for Sb recoil implanted samples. Ar^+ was the primary ion. The Sb thicknesses were: (a) 60 nm; (b) 90 nm; (c) 110 nm; and (d) 175 nm. Annealing was at 1100° C for 20 min. The arrows indicate the junction positions for samples (a)–(d).

dopant densities. This was done using the standard four-point probe technique. Profiling was made using anodic oxidation and etching. The dopant densities and their profiles were calculated based on the method of Plunket [7]. For a comparison, simulated profiles were calculated using the Boltzmann transport model [5]. It should be pointed out that the Boltzmann transport model, whilst proficient in accounting for the energy or momentum transfer of the particles in the collision process, does not take into consideration other effects, such as diffusion migration. It has been assumed that they do not occur simultaneously.

3. Results and discussion

Fig. 1 shows the measured sheet resistance profiles for Ar^+ implanted samples with different Sb thicknesses: 60, 90, 110 and 175 nm. The implant energy was 150 keV and the dosage was $1 \times 10^{15}\,cm^{-2}$. The samples were annealed at 1100° C for 20 min. Normally, most of the structural damage could have been removed. There were resistance peaks in all the profiles indicating the presence of depletion layers within the Si surface. The highest resistances, as well as the deepest peak, occurred when the Sb layer thickness was 110 nm. Also shown (in arrows) are the junction positions as extrapolated from the carrier density profiles.

Fig. 2 shows the computed carrier densities based on the sheet resistance profiles. The solid lines in the figures are the computed Sb profiles based upon the Boltzmann transport model [5]. For samples formed with thin Sb layers (< 100 nm), the measured profiles basically agreed with the computed results (for near unity yield) at mid range. Near the Si surface (within

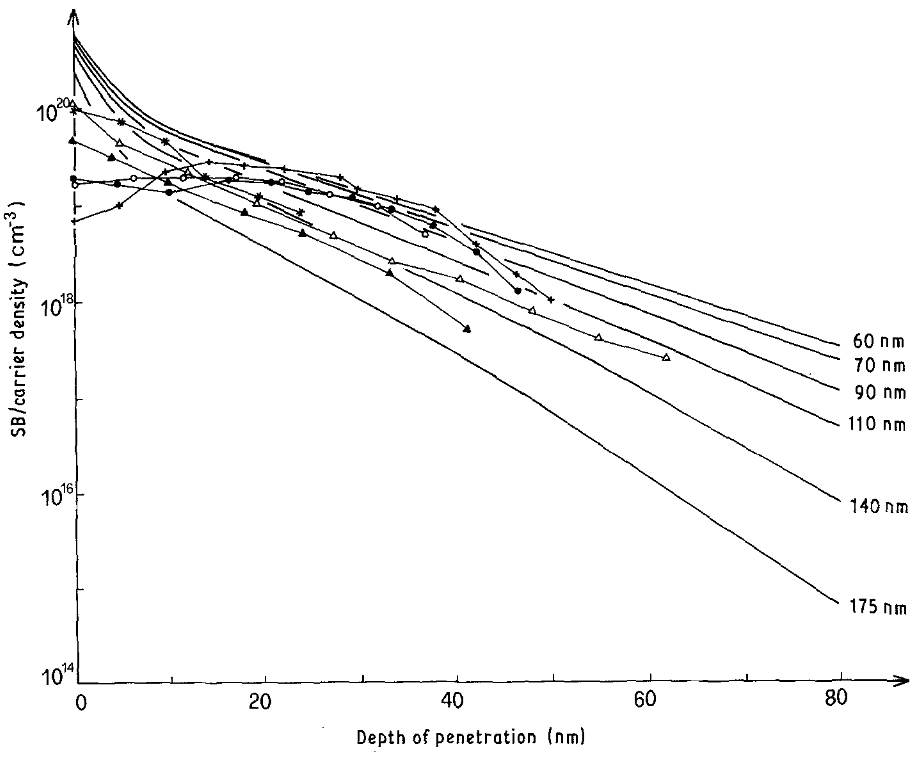

Figure 2 Carrier density profiles derived from Fig. 1 and computed from the Boltzmann transport model (solid lines). The Sb layer thicknesses were as labelled. Two additional profiles corresponding to Sb thicknesses of 70 and 140 nm were also included. (○) 60 nm; (+) 70 nm; (●) 90 nm; (△) 110 nm; (*) 140 nm; (▲) 175 nm.

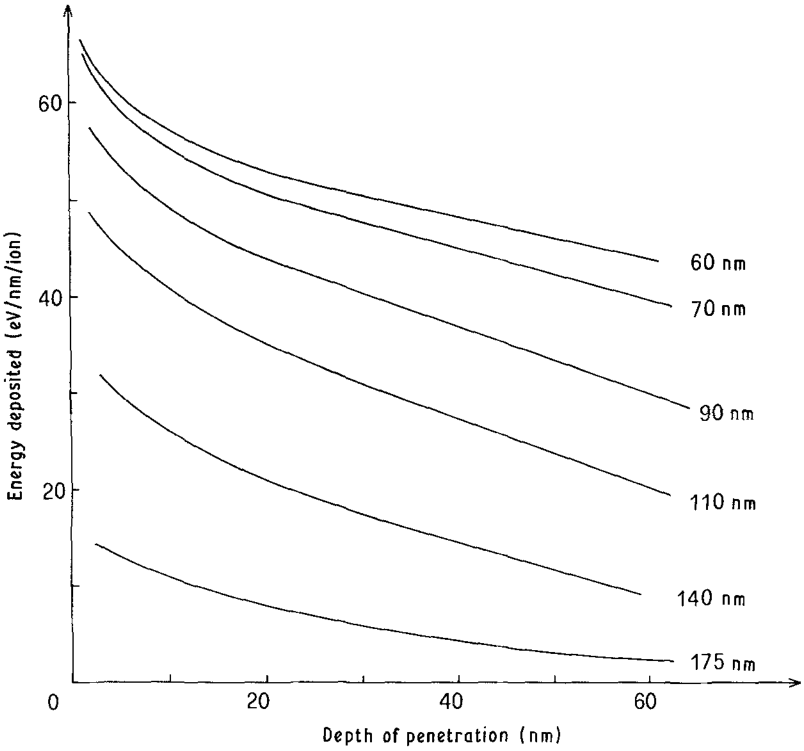

Figure 3 Energy deposition as a function of penetration into Si for different Sb layer thicknesses.

20 to 30 nm) as well as near the resistance peaks, the measured carrier densities were lower. For those samples with thicker Sb layers, there seemed to be much better agreement. Furthermore, the differences in the carrier densities near the Si surface appeared to vary with the Sb layer thickness and was smaller for the thicker Sb layers (like 90 nm). One possible explanation could be a much reduced mobility near the Si surface due to the high energy deposition. Fig. 3 shows a plot of the energy deposition by the incident ions as a function of penetration into Si for different Sb layer thicknesses. The energy deposited per nm was significantly higher near the surface for the thinner Sb layers. Assuming a threshold energy for the reduction in mobility to be 5 eV/nm/ion, the lowering of the carrier densities near the Si surface coincided closely with those regions of high energy deposition. As mentioned earlier, this problem did not exist for samples formed with thicker Sb layers.

The reason for the discrepancies between the measured and calculated carrier densities near the sheet resistance peaks for the samples, formed using thin Sb layers, was more intriguing. In these cases, the Sb profiles had already deviated from what would be expected from the Boltzmann transport equations. We suggest that the Sb atoms had redistributed during the annealing process, including possible out-diffusion at the Si surface [8]. An important factor for this to occur would be a highly damaged Si layer. This is met when the energy deposition is sufficiently large and according to Fig. 3, it would be much more important for samples formed with thin Sb layers. This might also explain the anomalous shallow depletion layers observed in the sheet resistance measurements for these samples. This is very important for shallow junction formation, since it implies some very close ties between damage effects (related to energy deposition), dopant redistribution during annealing and the observed electronic properties. The Boltzmann transport equation only takes into account particle distribution before and after collisions, whilst the sheet resistance profile measurements provided a more realistic account of the actual carrier distribution. Measurement of the I–V characteristics of some of the devices substantiated this point as p–n junction characteristics were only observed in samples formed with an Sb layer thickness greater than 170 nm [9]. For those samples with a smaller Sb layer thickness, Schottky barriers were measured. Further work is being carried out to study the C–V properties.

4. Conclusions

Recoil implantation of Sb is a complicated process and the resulting profiles critically depended on the extent of damage, as reflected in the discrepancies for the carrier density profiles. Excessive damage as related to the energy deposition could result in lowered mobility (apparently not removed even after heat treatment for a short period at 1100° C) and a damaged structure that could enhance dopant redistribution during heat treatment. All these effects are important for shallow junction formation and it appears that particular attention must be paid to minimize such implant damage effects if predictable junction properties are desired.

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