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# Damage effects in as-prepared recoil-implanted shallow p–n junctions

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This work investigated the damage effects in shallow Si $p^+$–n junctions formed by recoil implantation. By implanting through a thin aluminium film, it was possible to achieve very shallow p–n junctions (<100 nm). Using different implant dosages, both the junction depths as well as the damage densities were varied. *I–V* curves were used to study the electrical characteristics after low temperature heat-treatment at 450 °C. It was observed that the devices changed from Schottky diodes to shallow p–n junctions as the implant dosages increased. At the intermediate dosage, recombination current was found to be important. There were evidence that the densities of the recombination centers could be related to those of the displaced Si atoms. At the very high implant dosages, diffusion current dominated.

## 1. Introduction

The study of the electrical properties of shallow junctions is of interest for submicron device fabrication [1]. By contrast with lateral-scaling which leads to velocity saturation and other two-dimensional effects [2, 3], the current transport of a very shallow junction will be limited by tunneling and possibly other interface effects [4]. In the limit, for a metal-semiconductor junction, thermionic current will dominate [5]. This normally occurs at an emitter depth of less than 0.1 μm. For a highly-doped p–n junction, tunneling effect will also be important at about this thickness [6]. This work investigated the current transport in very shallow p–n junctions formed by recoil implantation [7]. Recoil implantation, or through-film implantation as it is often called, will produce a very shallow implant layer with a thickness that can be controlled by either changing the surface film thickness or by changing the implant energy. Depending on the desired profile, both the implant (primary) ions and the (recoil) atoms from the surface film can be the dopant. Fig. 1 shows a schematic of the recoil implant process. As with all implant processes, recoil implantation requires activation and damage-annealing. To a good extent, the pre-anneal damage is primarily determined by the kinetic energy of the incident ions.

In this work, shallow p–n junctions were formed on n-type Si substrates. Three different primary ions (with different masses) were used. The implant was carried out through a thin layer of Al (85 nm). Since Al is an acceptor in Si, the recoil atoms would also increase the surface dopant densities. The implant layer thickness was changed by varying the dosage. As far as possible, the experiment was designed to preserve the initial profiles. This was achieved by using only a brief heat-treatment at 450 °C in nitrogen. It was expected that the implant damage would only be partially-removed and that carrier activation would be somewhat small. *I–V* curves at different implant dosages were used to study the device characteristics. From the data, it was observed that device properties changed significantly with the implant dosage. At a low implant dosage ($< 10^{11}$ cm$^{-2}$), Schottky barriers were measured. This changed-over to the properties of shallow p–n junctions at the high implant dosages ($> 10^{15}$ cm$^{-2}$). At the intermediate implant range, recombination current became important. A correlation between the estimated densities of the recombination centers and those of the displaced Si atoms suggested the latter might be responsible for the recombination current.

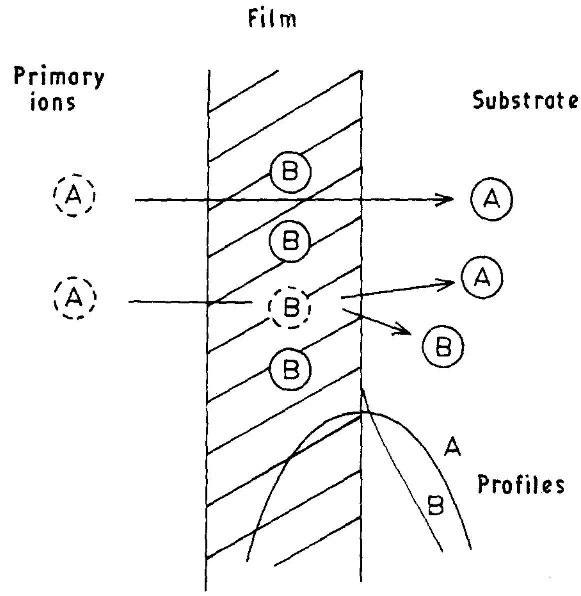


*Figure 1* Schematic of the recoil implant process. Atoms labelled "A" are the primary ions and those labelled "B" are the recoiled atoms. The "inset" shows the atom profiles.

## 2. Experimental details

N-type ⟨1 0 0⟩-orientated Si was used in this work and the resistivity was between 10–20 Ω cm. The wafers were cleaned using a standard IC procedure. Al containing 1% by weight of Si was deposited using an E-beam evaporator. The deposition rate was set at $4\,nm\,s^{-1}$ and the thickness was controlled to 85 ± 5 nm. Implantation was done using a Varian Extrion 200–1000 implanter. $Ar^+$, $B^+$ and $BF_2^+$ were used as the primary ions. Their atomic masses and the implant energies were listed in Table I. The implant energies were chosen such that the implant peaks would fall approximately at the Al/Si interface. This was known to facilitate maximum transfer of dopants across the interface. No pre-implant amorphisation was used since the Al film would to some extent act as a buffer. The detailed implant conditions were also listed in Table I. To minimise heating effects during implantation, the implant current was kept below 250 μA. After implantation, the residual Al was removed and additional Al was deposited to form the front contacts (circular contacts with 2 mm dia.). Back contacts were formed using a similar procedure. Before any measurements, the samples were heat-treated at 450 °C for 20 min in nitrogen. As expected, this would partially activate the dopants but it would not significantly disturb the as-prepared dopant profiles. The series resistances of the devices were measured and were removed from the electrical measurements.

## 3. Results

In our devices, both the recoil Al atoms and the boron atoms from the primary ions would give rise to p-type surface layers. Ideally, their contribution to the carrier densities should be the same once they were activated. The damage effects for the different primary ions, however, ought to be quite different since the kinetic energies of the primary ions were different. Because of the low activation temperature used (450 °C), it was expected that only a small fraction of the atoms would be activated. For instance, in [8], the percentage activation of Al at 450–500 °C was estimated to be less than 0.1% and the same figure for boron appearing in [9] was no more than 10%. An attempt had also been made to measure the carrier density profiles by surface resistivity measurements together with oxidation and etching [10]. The only reliable data were for the $Ar^+$ implanted samples at the highest implant dosages when the implant depth was measured to be less than 80 nm.

Fig. 2 shows the measured $I$–$V$ curves of the devices when implanted at different dosages. From the figures, one could easily identify the transition from Schottky diodes to shallow p–n junctions. This could also be related to the changes in the so-called "cutin" voltage. At the low implant dosages, the barrier heights for all the devices were measured to be about 0.76 eV. This was a value typical of Al/n-Si Schottky diodes [11]. Fig. 3a and b show how the ideality factors and the saturation current densities varied with the implant dosage. As observed, the ideality factors were high (> 1) and increased with increasing dopant densities. Similar observations were also reported for Au/n-Si Schottky diodes and were attributed to tunneling effects [12]. In most cases, an ideality factor between 1–2 normally implied the presence of recombination current. The increase in the saturation current densities at the intermediate implant range shown in Fig. 3b could also be due to an increase in the recombination current. Note the existence of a linear relationship between the saturation current densities and the implant dosages. At the higher implant dosages, we saw the peaks in the saturation current densities (except for the $Ar^+$ implanted devices) and the decrease in the ideality factors. Such changes were in line with the gradual transformation to diffusion-dominated current transport.

To examine the role of damage in these devices, it would be necessary to relate the damage densities to the electrical characteristics. Damage effects were exemplified by the production of point defects in the device and were often related quantitatively to the density of the displaced substrate atoms [13]. Experimentally, it was difficult to measure directly the damage profile and no such attempt was made in this work. Fig. 4 shows the simulated damage profiles for the devices assuming that the damage densities were the same as the displaced Si densities. The data were computed using the Boltzmann transport equation [14] at the dosage of $1 \times 10^{15}\,cm^{-2}$. As expected, the range of the damage profiles varied proportionally with the atomic masses of the primary ions.

TABLE I Some process parameters for the implant process

| | $B^+$ | $Ar^+$ | $BF_2^+$ |
|---|---|---|---|
| Atomic masses | 10.8 | 39.9 | 48.8 |
| Energies (keV) | 25 | 110 | 120 |
| Dosages ($cm^{-2}$) | | $10^{11}$–$10^{16}$ | |
| Al thicknesses (nm) | 85 | 85 | 85 |
| Maximum emitter depths (nm) (estimated[a]) | 100 | 250 | 120 |
| Damage range (nm) (estimated[a]) | 72.5 | 250 | 176 |

[a] Estimated from simulation based on the Boltzmann transport equation [14] with full activation.

## 4. Discussion

Recoil implantation would give rise to surface dopant layers at sufficiently high dosages. Thus, p–n junctions could be formed. For very shallow junctions, we expected the device properties to be affected by the interface and less-than-ideal characteristics might be measured. This was especially true in the case of recoil-implanted devices where at the interface, there would also be a high density of the recoil atoms. In this work, we observed the gradual formation of p-type surface layers as we increased the implant dosages. We also saw the changes from Schottky barriers to shallow p–n junctions. Because of the somewhat low heat-treatment temperature chosen, we anticipated considerable damage effects at the Si/Al interface. This was indeed reflected in the increase in

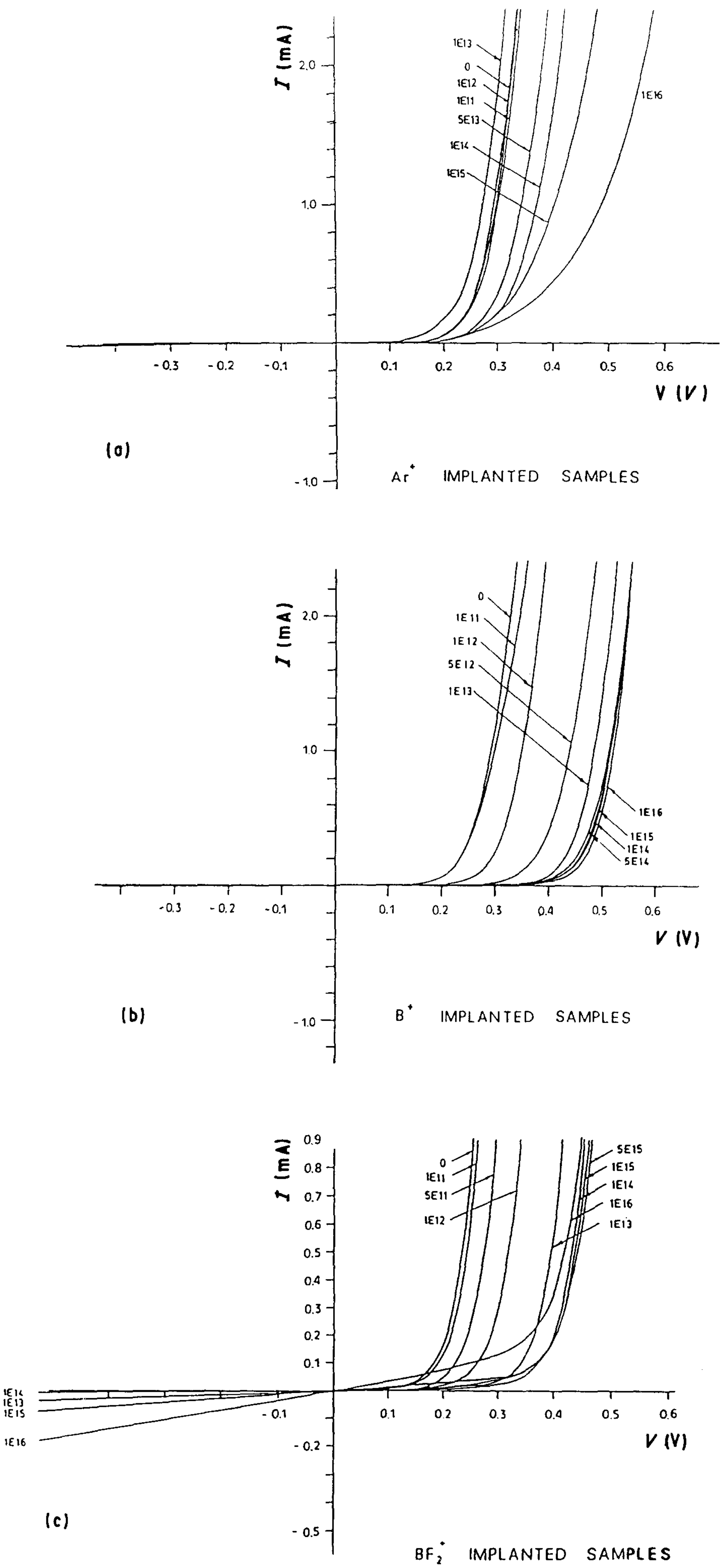


*Figure 2* *I–V* curves: (a) $Ar^+$, (b) $B^+$ and (c) $BF_2^+$ implanted devices. The dosages are as-labelled.

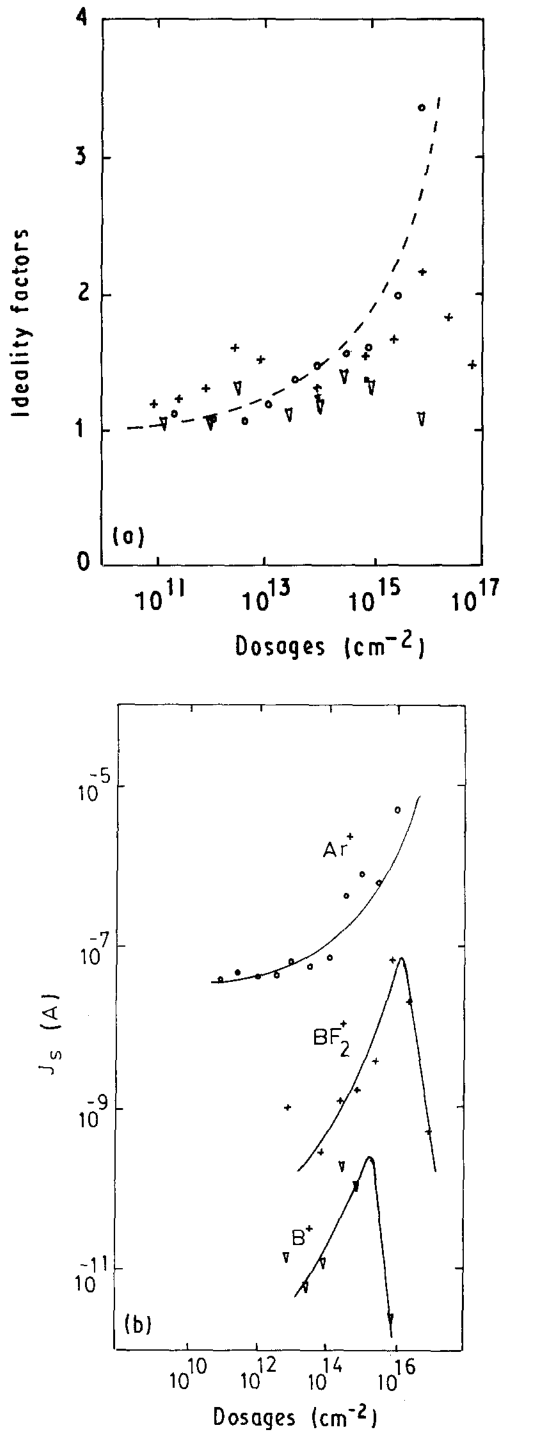


*Figure 3* (a) Ideality factors and (b) saturation current densities against the implant dosages. The labels indicate the type of primary ions used.

the ideality factors and the saturation current densities at the moderately high implant dosages.

One interesting question that could be raised regarding the formation of these shallow p–n junctions was what was the current transport at the intermediate implant range. To a first order of approximation, we saw the saturation current densities varied proportionally with the implant dosages. This could not be easily explained by either thermionic current or diffusion current. Recombination current, however, would give the right dependence [4, 15], whether tunneling was involved or not, if the densities of the recombination centers were proportional to the implant dosages. This of course would suggest a correlation between the densities of the recombination centers and the damage densities. Fig. 5 shows a plot of the saturation current densities for the $Ar^+$, $B^+$ and $BF_2^+$ implanted devices against the simulated displaced Si densities measured at a depth of 65 nm away from the Si surface (see Fig. 4). The implant dosages were $1 \times 10^{15}$ $cm^{-2}$. Note the linear relationship suggesting the presence of a damage-related recombination process. Thus, as far as current transport was

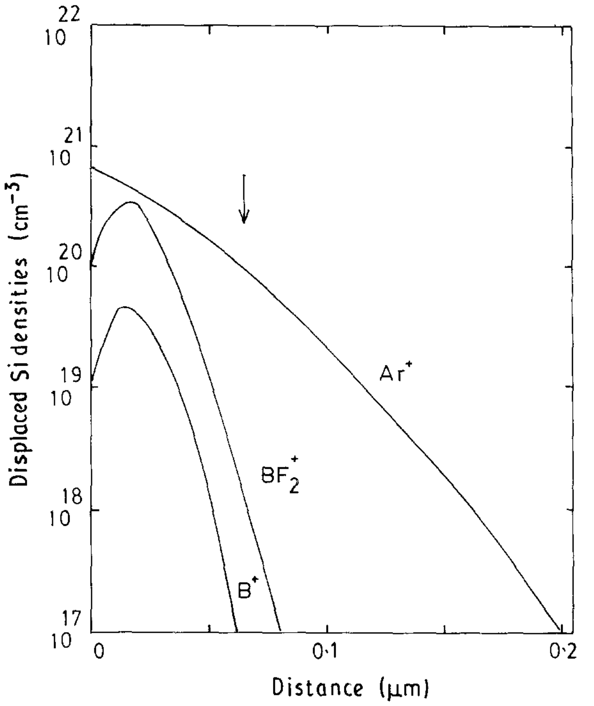


*Figure 4* Stimulated displaced Si profiles vs distance from the Si surface. The labels indicate the type of primary ions used.

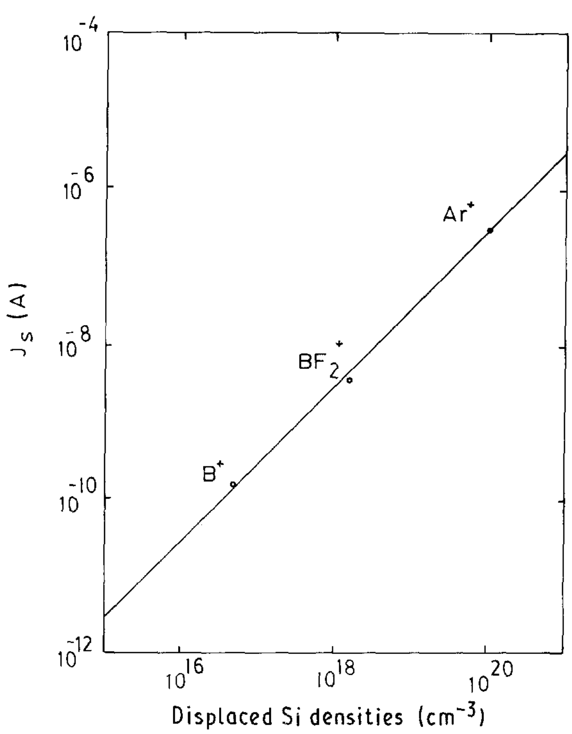


*Figure 5* Saturation current densities vs the displaced Si densities for the three different types of devices. The data were taken 0.065 μm from the Si surface (as indicated by an arrow in Fig. 4).

concerned, the variations of the saturation current densities could be related to the damage densities which, in turn, could be correlated to the densities of the displaced Si atoms.

At the very high implant dosages, diffusion current would become important as the junctions moved further away from the Si surface. For the lighter ions, this could significantly reduce the recombination current since the junctions would be located away from Si surface where most of the damage occurred. This might explain why we did not observe the saturation current density peak for the $Ar^+$ implanted device.

## 4. Conclusions

Recoil implantation provides a means to study the damage effects in very shallow p–n junctions. By implanting through an Al surface film, we reduced the implant depths as well as increased the surface dopant densities. For the three types of devices examined, we observed the transition from Schottky barriers to shallow p–n junctions as the implant dosages increased. To better understand the transition, we examined its current transport. Recombination current was used to explain the dependence on the implant dosages at the intermediate range as well as the correlation of the saturation current densities with the simulated damage densities. Such observations pointed to the importance of the implant damage in these devices and the possible advantage in the use of lighter ions in the recoil process.

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