# Electrical behaviour of arsenic implanted silicon wafers at large tilt angle

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*Abstract***— Two sets of silicon wafers were implanted with 60 keV arsenic ions at a dose of 5x10$^{15}$ cm$^{-2}$, using an Applied Materials SWIFT implanter. The first batch consisted of five silicon pre-amorphised wafers, whilst the second batch was implanted under the same conditions into <100> single crystal wafers. The tilt angle was varied over the range 0º - 45º. After implantation the samples were cut into smaller pieces and annealed in the range 800 to 1000 $^{o}$C for times up to 60 seconds in flowing nitrogen. Van der Pauw measurements of the Hall effect and resistivity were made to obtain values of the sheet resistance ($R_S$), Hall mobility ($\mu_H$) and sheet carrier concentration ($N_S$) as a function of the tilt angle. Electrical profiles were obtained from differential Hall effect measurements, whilst the retained dose was determined by Rutherford Back Scattering (RBS). The results show that the sheet resistance and the sheet carrier concentration are a function of the tilt angle and that pre-amorphisation results in a higher degree of electrical activation. A comparison of atomic and carrier concentration profiles as a function of tilt angle in conjunction with simulations are used to explain the observed results.**

***Keywords-component: tilt angle, Arsenic, RBS, Hall effect***

## I. INTRODUCTION

The ion dose has become a very difficult process to control as the angle between the beam direction and wafer normal increase [1]. High angle implants with a tilt angle from 30 to 60 degrees have became more and more important for implantation under masking structures and doping of non-planar structures such as trench sidewalls [2].

In order to dope the sidewalls of a trench it is necessary to perform angled ion implantation. In most cases, ion implantation is performed at 7º tilt in order to avoid channeling [3]. Increasing the tilt angle will move the dopant concentration near to the surface decreasing the junction depth. This affects both the sheet resistivity and the sheet carrier concentration. However it is important to understand how much dopant is retained in the wafers when the angle is changed and how this can effect the electrical properties of the implanted material. To investigate this effect, arsenic ions have been implanted into crystalline and pre-amorphised wafers to check if the pre-amorphisation could improve the activation of the dopant and to determine the retained dose as a function of angle of implant.

## II. EXPERIMENTAL

The first batch of 200 mm Si wafers were implanted at tilt angles of 0º, 15º, 30º, 45º and 0º twist with a nominal dose of 5x10$^{15}$ As$^{+}$cm$^{-2}$ and an energy of 60 keV. The second batch was pre-amorphised using 60 keV Ge$^{+}$ with a dose of 1x10$^{15}$ at/cm$^{2}$ prior to the arsenic implant. After implantation the samples were annealed in a Process Product Corporation RTP halogen lamp system.

The annealing was performed in nitrogen ambient in the range 800 to 1000 $^{o}$C for times of up to 60 seconds. Each wafer was cut into pieces for RBS Hall effect and resistivity measurements. Clover leaf shapes were made on the samples using a photolithography technique for van der Pauw measurements of the Hall effect and resistivity in order to obtain values of the sheet resistance ($R_S$), Hall mobility ($\mu_H$) and sheet carrier concentration ($N_S$) as a function of the tilt angle. Electrical profiles were obtained from differential Hall effect measurements, whilst the retained dose was determined by Rutherford Back Scattering (RBS) analyses using 1.5 MeV $^{4}$He$^{+}$ ions.

## III. RESULTS AND DISCUSSION

### *A. RBS measurements*

RBS analysis was performed on the two sets of samples. The first set of measurements were to estimate the retained dose on as-implanted samples, whilst the second set of measurements was performed on samples after annealing to determine the retained dose.

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TABLE I. RETAINED DOSE MEASURED BY RBS FOR ALL THE WAFERS AT DIFFERENT TILT ANGLE BEFORE ANNEALING

| Tilt angle (degrees) | Nominal dose ($10^{15}$ at/cm$^2$) | Retained dose ($10^{15}$ at/cm$^2$) | Pre-amorphised | Crystalline |
|---|---|---|---|---|
| 0 | 5.00 | 4.96 | Yes | |
| 15 | 5.00 | 4.97 | Yes | |
| 30 | 5.00 | 4.95 | Yes | |
| 45 | 5.00 | 4.98 | Yes | |
| 0 | 5.00 | 4.98 | | Yes |
| 15 | 5.00 | 4.97 | | Yes |
| 30 | 5.00 | 4.96 | | Yes |
| 45 | 5.00 | 4.96 | | Yes |

TABLE II. RETAINED DOSE MEASURED BY RBS FOR ALL THE WAFERS AT DIFFERENT TILT ANGLE AFTER ANNEALING AT 800 °C

| Tilt angle (degrees) | Nominal dose ($10^{15}$ at/cm$^2$) | Retained dose ($10^{15}$ at/cm$^2$) | Pre-amorphised | Crystalline |
|---|---|---|---|---|
| 0 | 5.00 | 4.46 | Yes | |
| 45 | 5.00 | 4.44 | Yes | |
| 0 | 5.00 | 4.47 | | Yes |
| 45 | 5.00 | 4.45 | | Yes |

Results in Table I show that for as implanted samples the implanted dose ($5x10^{15}$) is equal to the retained dose (average of $4.97x10^{15}$ ), within experimental error. Thus we can deduce that no sputtering or backscattering occurs. From Table II we can deduce that the retained dose has reduced by about 10% to $4.46x10^{15}$ cm$^{-2}$ on average for all the wafers after annealing. This is a consequence of the out-gassing of arsenic during annealing. The absolute error in the retained dose for each single measurement was less than 3%.

*B. Electrical results*

The Van der Paw technique was employed to measure the sheet resistance, Hall mobility and the sheet carrier concentration. Figures 1 to 6 show the sheet resistance, sheet electron concentration and Hall mobility as a function of the tilt angle for pre-amorphised and crystalline wafers for different annealing temperatures and times.

At this level of doping for arsenic the junction depth controls the sheet resistivity [4]. So as soon the tilt angle increases the junction depth decreases and the decrease in junction depth results in a higher sheet resistivity [5].

The figures show that the mobility is approximately constant with tilt angle and that the sheet resistance tends to increase and the sheet carrier concentration tends to decrease with increasing tilt angle. The three variables, $R_S$, $\mu_H$ and $N_S$ are linked together by:

$$\mu_H = \frac{1}{q}\frac{1}{R_S N_S}$$

where q is the electronic charge.

Thus the results are consistent in that we find that $R_s$ is inversely proportional to $n_s$, with constant mobility.

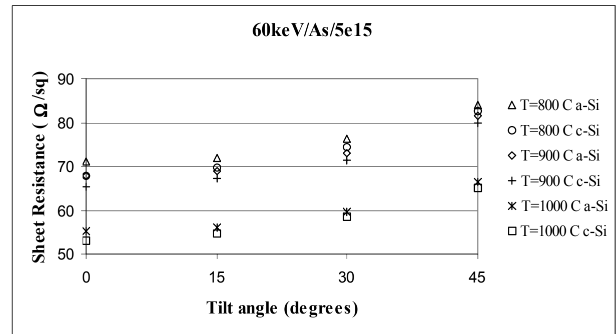


Figure 1. Sheet resistance as a function of the tilt angle for 60 keV $As^+$ at different annealing temperatures for time of annealing of 30sec

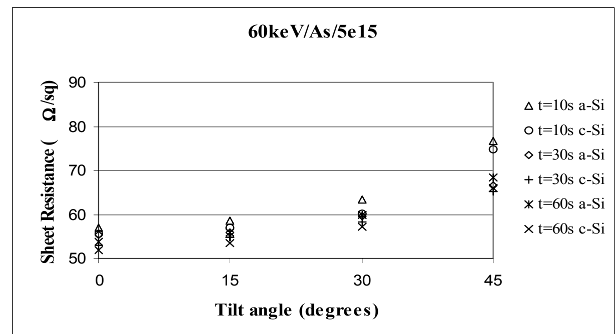


Figure 2. Sheet resistance as a function of the tilt angle for 60 keV $As^+$ at different annealing times for a temperature of annealing of 1000ºC

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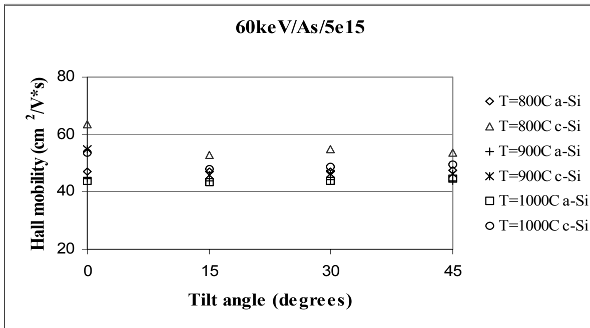


Figure 3. Hall mobility as a function of the tilt angle for 60 keV $As^+$ at different annealing temperatures

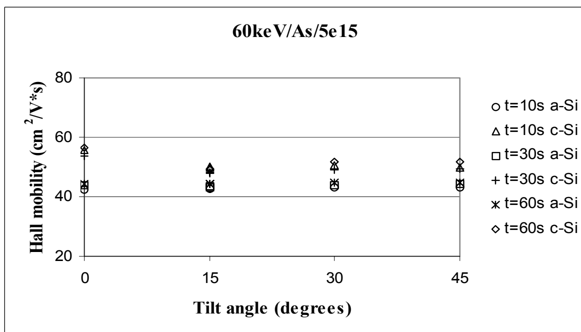


Figure 4. Hall mobility as a function of the tilt angle for 60 keV $As^+$ at different annealing times

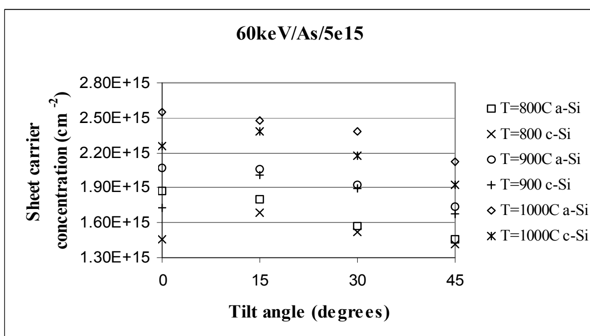


Figure 5. Sheet carrier concentration as a function of the tilt angle for 60 keV $As^+$ at different annealing temperatures

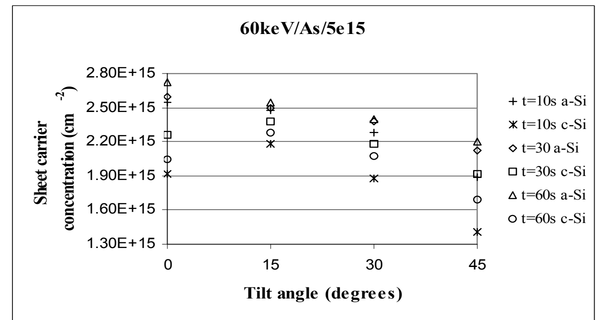


Figure 6. Sheet carrier concentration as a function of the tilt angle for 60 keV $As^+$ at different annealing times

From figures 5 and 6 we can observe that samples which have been pre-amorphised with germanium have shown a better activation for all the annealing temperatures and times. Pre-amorphisation with germanium also results in a shallower junction depth and a better electrical activation [6].

### *C. Differential Hall Measurements (DHM)*

Simulations (using MonteCarlo code) [7] of the atomic profile after annealing were compared with DHM measurements performed to estimate the amount of electrically active dopant in the silicon.

The DHM measurements give us the distribution of the active dopant as a function of depth. The area under the curve is equal to the fraction of the retained dose that is electrically activated. Table III summarises the results. The "Hall" data refer to the sheet carrier concentration as a fraction of the retained dose after annealing, whilst the "DHM" data refer to the integrated area beneath the electrical profile of figure 7. The magnitude of these two parameters is very similar showing the consistency of the data and measurement techniques. The Silvaco simulations of the electrical activity (Table III) overestimate the electrical activity especially at high tilt angles. We note from fig. 7 that only a fraction of the retained arsenic is active after annealing because at high doses arsenic tends to form precipitates [8].

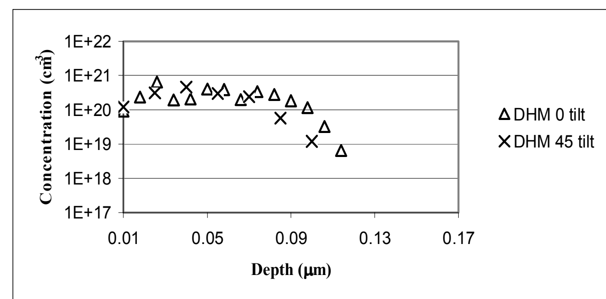


Figure 7. Carrier concentration profiles of 60 keV As at 0º and 45º tilt; dose $5x10^{15}$ $cm^{-2}$ after annealing for 30 sec at 1000 ºC

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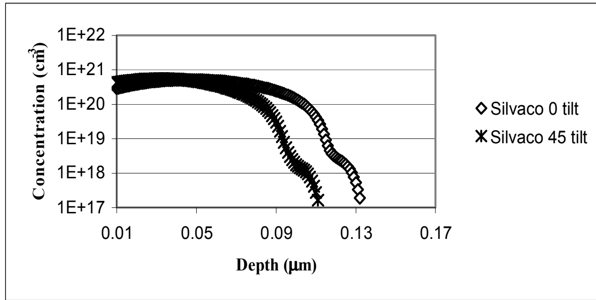


Figure 8. Silvaco simulation of 60 keV As at 0º and 45º tilt; dose $5x10^{15}$ $cm^{-2}$ after annealing for 30 sec at 1000 ºC

TABLE III. ACTIVAVATION OF IMPLANTED DOPANT WITH DIFFERENT TECHNIQUES FOR 60 KEV $As^{+}$ AFTER ANNEALING AT 1000 ºC FOR 30 SEC

| Tilt angle (degrees) | Hall (%) | DHM (%) | Silvaco (%) | Pre-amorphised |
|---|---|---|---|---|
| 0 | 56.7 | 58.2 | 73.4 | Yes |
| 45 | 47.1 | 48.0 | 67.6 | Yes |
| 0 | 50.2 | 49.8 | 82.0 | No |
| 45 | 40.2 | 41.1 | 58.0 | No |

## IV. CONCLUSION

The sheet resistance and sheet carrier concentration as a function of the tilt angle have been investigated. It was found that they are a function of the tilt angle. Thus for high tilt angle the sheet resistance increases and the concentration of activated dopant decreases. At the same time the Hall mobility remains approximately constant for all the tilt angles. By comparing implantation into pre-amorphised and crystalline wafers it was found that wafers pre-amorphised with germanium show a higher activation compared to crystalline wafers.

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