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VARIATIONAL EFFECT OF ELEVATION ON THE RANGE OF ENERGETIC BORON IONS IN AN AMORPHOUS SILICON TARGET

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ABSTRACT
The work aims at exploring the effects of varying implantation elevation on the penetration depth (Range) of energetic ions in an amorphous target using SRIM-2008.03 simulation package. The range was observed to decrease from 229 Å to 118 Å with increasing elevation (0^0 - 88^0). The decrease in range was attributed to two distinct but simultaneous phenomena; the increase in surface backscattering of impinging ions due to head-on collision with target atoms and the decrease in number of vacancies created within the silicon crystal lattice due to the triggered cascade of collision events by adjoining silicon atoms.
Keywords: Implantation, range, scattering, SRIM-2008.03 package, surface sputtering, vacancies.

INTRODUCTION

Ion implantation, as an alternative to diffusion, is used to produce a shallow surface region of dopant atoms deposited into a target material. It is a materials engineering process by means of which energetic ion species are accelerated in an electrical field and impacted into a solid. It can as well be seen as an effective technological tool for introducing single impurities into the surface layer of a solid target to a depth of several micrometers (Ziegler and Lever, 1985). In this ion-solid interaction, ions penetrate through the materials and slow down to some extent into the materials due to electronic and nuclear energy loses (Limandri *et al.*, 2014). Since its first deployment in 1950's to few decades back, ion beam implantation has only been known as a process used for damaging the surfaces of bulk materials and doping of semiconductors to fabricate p-type or n-type materials. However, the process has later been proven as a reliable technique to tune the properties of bulk materials for specific applications (Mikšová *et al.*, 2017). Nevertheless, inherent material properties can be modified based on appropriate selection of ion species, ion energy, substrate temperature, and ion fluences among other parameters. Energetic ions usually considered for this process are mostly of energies in the range from few KeV to hundreds of MeV and are primarily produced from different ion sources. These ions are then extracted from the generation chamber and accelerated up to required energies according to the intended applications. For surface treatment of solids and semiconductors, usually low energy ions (in KeV ranges) are applied (Arista, 2002). This is because, recently, a Focused Ion Beam (FIB) system was developed and categorized as low-energy system which enables heavy ion medium micromachining to fabricate micro- and nano-devices. Medium energy ions, from medium energy electrostatic accelerators, are used for proton beam writing as well as synthesis and modification of thin films. High energy protons (swift heavy ions) having hundreds of MeV energies are applied for surface modification and the study of the intrinsic physical properties of thin films (Ahmed and Akram, 2017). Although ion implantation is widely used in both research laboratories and industries, its underlying physics is quite complicated-whose fundamentals are in the theory of atomic collisions; first established by the great physicist and Nobel laureate, Neils Bohr, more than a century ago (Suzuki, 2014).

In the context of this research, ion beam implantation -as a low temperature process- is used to alter the physical, chemical and/or electronic properties of an amorphous silicon target. The implanted Boron ions pass through the target, decelerate by transferring their energies to the target atoms, and finally halt at a certain depth (range) 0-1 μm below the surface. Thus, ion implantation is basically a surface or near-surface processing technique. Because energetic ions have stronger interactions with target atoms, they penetrate much less deeper in matter than do electrons, for the same implantation energy (Smith, 1997).

An important edge of this process over others, especially chemical deposition techniques, is that it provides precise control over the amount of dopants as well as the concentration profile and lateral dimensions in device fabrication. The resultant high degree of uniformity and reproducibility have made it possible to fabricate erudite devices and integrated circuits with high yield and tight tolerance. And for the fact that it is a low temperature process that is not constrained by thermodynamic considerations, it does not require any heat-resistant equipment to implant any species of ion (Zhang, 2002). However, despite all the favorable features, ion implanters are very expensive and complex to handle (Dapor, 1990).

During implantation, the coulombic interaction (due to scattering events) of an energetic ion with the atoms and electrons of a target material makes the ion to lose its energy and consequently gets slowed down at some location beneath the surface of the substrate (Zhang, 2002). The event of slowing down of this energetic ion is called "stopping" and that of energy lose determines the depth of penetration (range) of the ion into the target as well as the amount of damage (disorder) created in the lattice (Arista, 2002).

Because the target constitutes of both nuclei (atoms) and free electrons, the ion collision is usually separated into two major components; ion-nucleus (atom) and ion-electron interactions. Consequently the slowing down of the ions is categorized into two dominant energy, loss mechanisms namely; nuclear energy loss and electronic energy loss involving ion-nucleus and ion –electron interactions respectively (Dresselhaus and Kalish, 1992).

MATERIALS AND METHODS

The software utilized was the Stopping Range of Ions in Matter (SRIM 2008.03 version) and the type of calculation chosen was "Detailed Calculation with full Damage Cascade (DCDC)" (Ziegler *et al.,* 2010). Amorphous target was used (precisely Silicon, Si) unto which energetic Boron (B) ions were implanted. 10,000 boron ions (5 KeV), were implanted into a 1000 Å (100 nm) thickness of the silicon target at varying angles of incidence (implant elevation, θ). Other quantities of interest that form part of the input parameters for executing the calculation include; Atomic number of target, atomic number of ion, atomic weight of target, atomic weight of ion and target density. Upon successful execution, output text files involving backscattered ions, transmitted ions, vacancies created in the target, longitudinal/lateral ranges (depths of penetration), energy lost by ions and sputtering yield were extracted from the package and processed using OriginPro 2018.

RESULTS AND DISCUSSION

Table 1 depicts the data obtained from the implantation of energetic Boron ions into the thin layer (100 nm) of amorphous silicon target. The data represents the range (in angstrom), the counts of vacancies created in the target and backscattered ions with respect to varying implantation elevations.

S/N	Elevation (^{0})	Backscattered Ions (count)	Vacancy/Ion (count)	Range (Å)
1	0	441	99.8	229
2	4	447	99.8	229
3	8	449	99.8	227
4	12	472	99.7	224
5	16	534	99.7	221
6	20	546	99.7	217
7	24	620	99.5	214
8	28	684	99.0	208
9	32	792	98.8	203
10	36	900	98.5	195
11	40	1008	98.0	190
12	44	1182	97.2	183
13	48	1377	96.3	177
14	52	1625	95.4	167
15	56	1941	94.1	160
16	60	2280	92.1	155
17	64	2701	89.0	147
18	68	3169	86.0	142
19	72	3644	82.5	134
20	76	4311	76.9	130
21	80	4957	69.8	125
22	84	5868	59.2	121
23	88	7139	41.5	118

From the above table, it can be seen that at 0^0 elevation, the range was 229 Å but decreases almost linearly with increasing elevation. The range keeps diminishing until the lowest recorded value (118 Å) is attained at maximum recorded elevation (88^0). The decrease in range (at increased elevations) can be attributed to two important phenomena; a surface phenomenon involving the backscattering of impinging boron ions by the surface atoms of the target and a sub-surface phenomenon involving the creation of vacancies within the volume of the target by the penetrating energetic ions. Initially (i.e. at $\theta = 0^0$), energetic boron ions arrived normal to the target surface (i.e. vertically). This vertical ion-atom scattering knocks down the near-surface silicon atoms beneath the surface which eventually leads to cascades of collision events within the target thereby providing free channels (due to vacancy creation) in the silicon lattice for ions to penetrate. Large number of successfully implanted boron ions will create more vacancies in the lattice.

Figure 1 shows the variation of the depth of penetration of the energetic ions (range) in the target with implantation elevation.

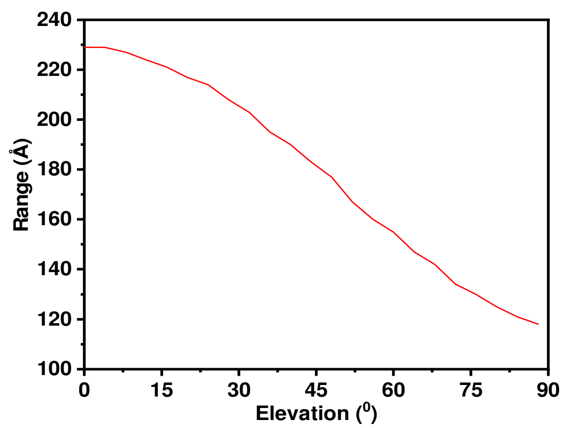

Fig 1: Variation of ion penetration depth (range) with implantation elevation.

On the other hand, fewer boron ions got backscattered due to continuous implantation along the same path (see fig. 2(a)). As the elevation increases (i.e. at $\theta > 0^0$), surface and near surface atoms are scattered at angles greater than 0°. At this instance, surface sputtering of target atoms also comes into play in addition to backscattering. In consonance with the laws of reflection, the number of backscattered ions increases drastically thereby lowering the frequency of collision events within the silicon target (see fig. 2(b)). Since in this case, fewer atoms got implanted due to surface scattering/sputtering, less vacancies will be created in the silicon lattice thereby decreasing the channels of travel for the penetrating ions. Consequently, the boron ions have fewer channels to propagate resulting in the observed decrease in ionic range.

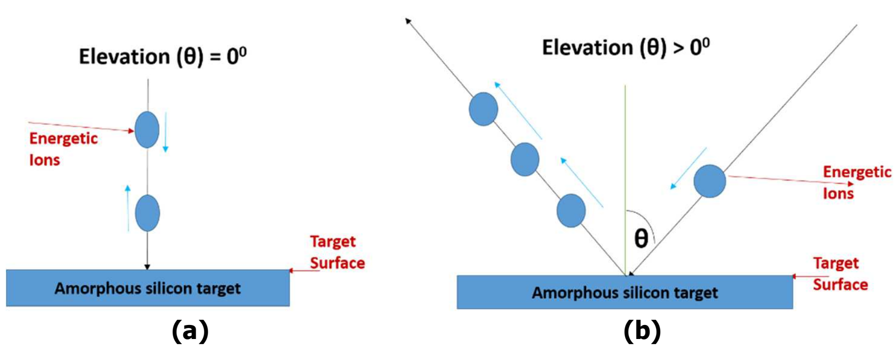

Figure 2: Backscattering of boron ions by target's surface atoms: (a) at $\theta = 0^0$ and (b) at $\theta > 0^0$.

CONCLUSION

The work explored possible effect(s) of varying elevation angles of an implanter during the implantation process involving energetic ions. Energetic boron ions were implanted at varying angles (0-88^0), but at fixed energies, into a single layer of amorphous silicon. The depth of penetration (range) for each elevation was evaluated. The effect of these variations on backscattered ions as well as vacancies created per ion were concurrently observed. The penetration depths of boron ion species were found to decrease with increasing elevation. This decrease in depths of penetration were attributed to backscattering of the vertically impinging ions due to collisions with target atoms at the surface and the reduced frequency of collisions with the atoms within the silicon lattice as a result of decreased vacancy creation. Hence an inverse relation was established between elevation (**θ**) and range (**R**).

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