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Ellipsometry and RBS Characterization of Temperature Dependent Silicon Ultra-Shallow Junctions for Sub 10 nm Applications

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ABSTRACT

The present paper is aimed to study the quality of the material after undergoing a complete cycle of formation of electrically stable ultra-shallow junction as a result of proposed ion implantation and annealing schedules. Hence Spectroscopic Starting pre-amorphized Silicon (Si) wafers were co-implanted with carefully chosen ion species such as indium (In) and Carbon (C) at 70 and 10 keV energy, respectively. The samples were subsequently annealed in pre-designed temperature processing window ranging from 600°C to 800°C. The post implantation and post annealing electro-optical Ellipsometric parameters and Rutherford Backscattering measurements of the samples directly affecting from the radiation-induced damage and its temperature dependent recovery show the maintainability of the junction so formed for use in CMOS devices, particularly for sub 10 nm technology nodes.

KEY WORDS: Carbon, CMOS, Indium, Low thermal Budget, Ultra shallow junctions

1. INTRODUCTION

Ultra Shallow Junction (USJ) formation in Si-CMOS technology is difficult to control. Fabrication of CMOS transistor by ion implantation with n-type and p-type transistor causes technological problems like channeling and TED. The formation of ultra-shallow junctions below 45 nm have been reported in literature by using various other combinations of dopants such as Ge+BF_2, Ge+BF_2+F, Ge+C+BF_2, C+F, B+C etc. The implantation of ion species heavier than boron, such as indium, has recently achieved new interest. When implanted, produces very shallow distribution with quite abrupt atomic profile. However, indium has low solid solubility and poor electrical activation which can be increased up to 50% when co-implanted with C. In this way it becomes possible to achieve higher value of electrical activation at lower temperatures due to its ability to trap Si-self interstitials and prevent them from deactivating indium to achieve junctions that are ultra-shallow, abrupt and highly activated [1,6].

Quantitative information such as junction depth (Xj) and electrical properties like doping concentration, sheet resistance and mobility are required to accurately predict their final behavior after electrical activation. It is also important to ascertain the maintainability of the material properties of the junction after a certain process recipe is employed in fabricating the Ultra Shallow Junctions for CMOS nano-electronics.

It is with this objective that we have studied the electro-optical properties of the nano-scale junctions and the substrate after the implementation of our proposed scheme comprising of ion implantation as key process step. We have employed Spectroscopic Ellipsometry (SE) technique to study the optical properties of such junctions. SE is unconventional but one of best non-contact, non-destructive tool SE is traditionally used in the Ultra–Violet, visible and near IR wavelength regions (250–1850 nm) for the measurement of layer thicknesses, refractive indices and carrier concentrations [2-6].

Besides SE, Rutherford Backscattering Spectroscopy (RBS) is also a powerful tool to characterize defect densities, thickness and structures in the near surface region of such thin layers. RBS is quantitative without the need for reference samples, nondestructive, has a good depth resolution of the order of several nm, and a very good sensitivity for heavy elements of the order of parts-per-million (ppm). The analyzed depth is typically about 2 μm for incident He-ions and about 20 μm for incident protons. A target is bombarded with ions at an energy in the MeV-range (typically 0.5–4 MeV), and the energy of the backscattered projectiles is recorded with an energy sensitive detector, typically a solid state detector. RBS allows the quantitative determination of the composition of a material and depth profiling of individual

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elements. Radiation damage introduce during RBS by the analyzing beam itself, but it is important to carefully chose the analyzing parameters, like total charge collection on one analyzing spot, to minimize radiation damage [7]. Thickness measurement results by RBS are also reported in literature [7-10]. Hence we have used RBS and Ellipsometry to determine the junction depth.

Our aim for the present studies is the formation of abrupt ultra shallow junction below 45nm with indium and carbon co-implantation in pre-amorphized silicon. The junctions so formed have been characterized by SE and RBS technique to efficiently analyze the shallowness of the junction under various thermal budget conditions. Our study is further aimed to provide an insight of quality of the material retained after undergoing the proposed implantation-annealing schedules for the formation of electrically stable ultra shallow junctions. This attribute in terms of electro-optical parameters is highly desirable to evaluate and analyze as it is directly linked with the post-processed junction performance when used in CMOS operations under various temperature regimes.

The major findings presented in this paper includes (a). The establishment of junction at 9nm- 60nm depth that was controlled by using appropriate thermal budget and verified by two independent opto-electronic techniques. (b). The optical properties of such junctions are almost uniform after the annealing at temperatures between 600 – 800 ^{O}C.

Rest of the paper has been organized as follows: Methodology and experimental setup with a brief introduction of the characterization tools used have been given in the next section followed by the results and discussion and concluding remarks in the following sections subsequently.

2. EXPERIMENTAL

Commercially grown, CZ p-type Si wafers of (100) orientation with initial resistivity between, 4-7 Ω/square were processed according to pre-designed implant recipes. In order to enhance the degree of electrical activation, the Si substrate samples were pre-amorphized with Si at an energy of ~500eV and a fluence of ~5×10^{15} at/cm^2. Pre-amorphized wafers were then implanted with 5.7×10^{14} indium at/cm^2 at 8° tilt and 24° twist having 70 keV energy. Carbon atoms have been co-implanted at the same angles with 10keV energy and fluence of 3.4×10^{15} at/cm^2. The processed wafers were then diced into squares of 1-1.5cm^2 sizes and subsequently subjected to Rapid Thermal Annealing (RTA) between 600 and 800°C for 60s dwell and carefully designed ramp-up time. These electro-optical measurements were performed at room temperature with a rotating compensator Ellipsometer of J. A. Woollam that measures the change in the polarization state of light when it reflects from the surface of a sample [2, 6]. The values of ellipsometric angles as a function of the wavelength for incidence angle at ~70 degree were measured for crystalline Silicon before and after indium plus carbon co-implantation. We have extracted thickness of implanted layers using one layer model which consists of one standard doped silicon layer on conventional silicon substrate to efficiently focus the measurement on active regions where ultra shallow junctions are stably formed and electrically activated. The measured values from Ellipsometer, (ψ) and (Δ) as shown in fig. 1 were directly used to determine absorption coefficient (α), refractive index (n) and effective junction thickness (X_j) using the expressions deduced after reference 5. In our case a 2-4 MeV He^{++} ion beam has been used with scattering angle ϕ=170° to perform RBS measurements. In all cases the beam was normal to the sample. The scattered particles were analyzed with a solid state detector located about 10 cm from the target with a solid angle 2.74 msr. The detector resolution is between 15 and 20 keV and the multichannel analyzer was set with a channel width at 5keV. All the spectra were recorded under routine experimental conditions on Tandem Accelerator Facility in National Centre for Physics (NCP), Islamabad.

3. RESULTS AND DISCUSSION

The experimental conditions to determine the refraction and absorption coefficients are set in such a way to focus the active device region of the In+C co-implanted silicon samples both in as-implanted and post annealed cases. The refraction and absorption coefficients determined in all such cases are presented in fig. 2. Fig. 2 provides an insight to the relationship of refractive index versus wavelength for Si substrate and as-implanted as well as annealed samples. It may be noticed that refractive index of the annealed samples remain almost constant at wavelengths between 400 to 900 nm for samples annealed at 600, 750, and 800°C temperature studied. The increase in the refractive index for as-implanted samples is thought to be due to the thermo-optic effects in which the phonons and electrons modify the refractive index undergoing a certain physical process (such as ion-beam induced damage) affecting the interaction of light with the material [11]. Fig.2 further shows the behavior of absorption coefficient for Si substrate, as implanted and annealed samples with respect to various wavelengths. It may be noticed that without having any extra ordinary variation in the behavior, the absorption coefficient (α) is almost maintained in the whole range of spectrum after annealing at various temperatures. This, however, is lower than the value of α for as-implanted samples. Indium absorption coefficient at 600°C decreases more than 750°C because of the behavioral difference of Indium at 600-650°C. Absorption coefficient at 800°C (and possibly above) withstands the trend and decreases due to possible free carrier absorption dominance in this range. For getting best performance of ultra-shallow junctions in CMOS and consequent efficient operational parameters such as response time and higher speed, absorption coefficient should be high i.e. larger number of photons should be absorbed in the depletion regions of the device. The relative depth to which photons penetrate is a function of its wavelength [12]. Initially the wafer was pseudo-amorphous (as implanted) so its absorption was high and reflectivity was low, but absorption would change as a function of time as the implant damages were annealed out. Fig.3. Shows a spectrum for He^{++} ions backscattered at an angle of 170° from the active region of In+C co-implanted p-type Si samples after annealing at different temperatures (600°C, 750°C and 800°C). Indium peaks were detected at 2.085 MeV, while Carbon peaks were detected at 4.267 MeV. These spectra were used to calculate the junction depths in as-implanted and annealed In+C co-implanted p-type silicon devices. We have deduced thickness of the active region from Fig. 3 and shown in Fig. 4. Fig.4. shows the comparison of junction depths obtained from ellipsometry and RBS. At lower temperatures (600°C -750°C) both the techniques show good agreement for thickness measurement near about 10 nm with standard deviation of lesser than 5%. This provides a statistical analysis of the reliability of a stable ultra shallow junction formed using a pre-designed implant annealing recipe. This further suggests that the stability of shape abruptness of the junction and the dopant profile activated under a certain thermal condition is grossly dependent on a carefully chosen time–temperature annealing cycle and the physical behavior of the dopants implanted in the junction matrix. Thus in our case at temperatures greater than 750°C, the standard deviation increases.

4. CONCLUSION

An ultra shallow junction has been achieved with indium and carbon co-implantation in pre-amorphized silicon. The junction depths between 9nm-60nm have been controlled through appropriate thermal budget and verified by two independent competitive and non-destructive techniques. It has been shown that the junction remains stable undergoing post implant thermal cycles between 600 and 800 ^{0}C while achieving the depths between 9nm and 60nm. The quality, shape and profile of the ultra shallow junction as exhibited by electro-optical parameters in this study may have ramifications for device engineers while fabricating CMOS on sub 10nm technology nodes.

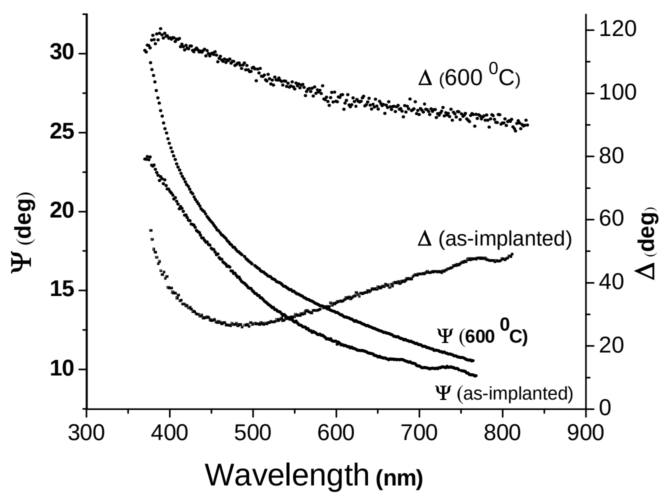

Fig.1: The spectra of ellipsometric angles ψ and Δ as a function of light wavelength measured at incidence angle 70° for In+C co-implanted Si USJs. Data points for as-implanted and annealed samples at temperature ranging from 600°C to 800°C are shown.

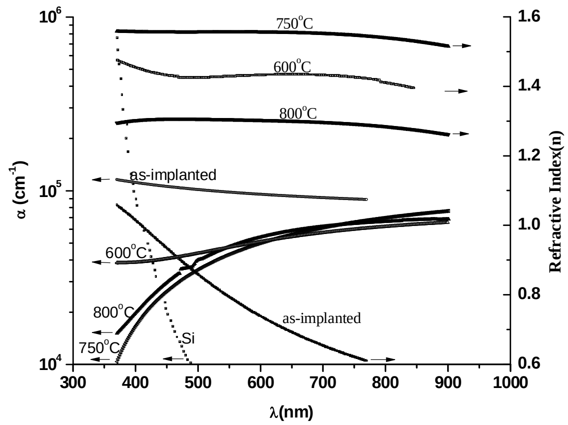

Fig.2: The variation of refractive index and absorption coefficient with increasing wavelength for as-implanted and annealed samples for In+C co-implanted Si USJs.

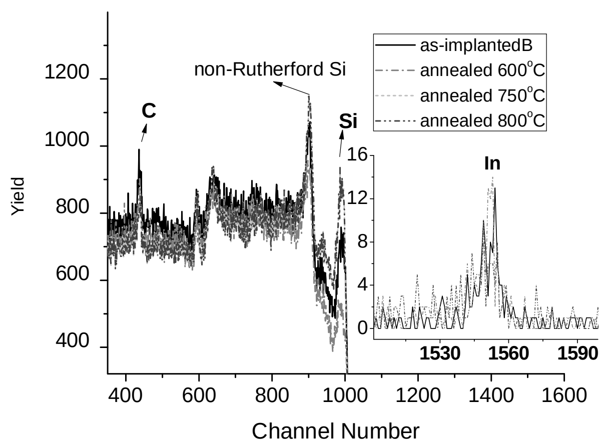

Fig.3: RBS spectrum recorded for He^{++} ions incident on the In+C co-implanted p-type Si substrate showing a comparison of as implanted and annealed results of RBS yields. The C, Si and In peaks are also identified.

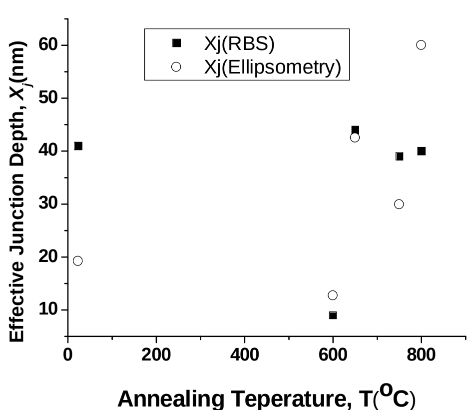

Fig.4: The USJ's effective junction depth obtained for Indium plus carbon co-implanted Si devices on the basis of measurements done with ellipsometry and cross-checked by RBS. Both the techniques show junction depth of sub 10 nm achievable at post-implant annealing temperature of 600°C.

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