Applied Surface Science xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Shallow junction characteristics due to low temperature BGe molecular ion implantation into silicon

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ARTICLE INFO

Article history:
Received 3 November 2013
Received in revised form 12 April 2014
Accepted 16 April 2014
Available online xxx

PACS:
61.72.Tt
61.80.Jh
81.40.Ef
85.40.Ry
84.37.tq
73.40.Kp

Keywords:
Molecular ion implantation
Shallow junction
Annealing
Transient-enhanced diffusion
Junction depth
Sheet resistance

ABSTRACT

In this study, shallow junction characteristics produced by implanting 2×10^{15} cm^{-2} 77 keV BGe molecular ions into n-type <1 0 0> silicon wafers at liquid nitrogen temperature (LT) and room temperature (RT) were investigated. Post-annealing methods employed consisted of furnace annealing (FA) at 550 °C for 0.5, 1, 2, and 3 h and rapid thermal annealing (RTA) at 1050 °C for 25 s. In particular, one-step (FA) and two-step (FA + RTA) post-annealing treatments were conducted. The shallow junction characteristics that were examined included junction depth, sheet resistance, crystalline recovery, and damage microstructure, and were measured using secondary ion mass spectrometry (SIMS), a four-point probe, Raman scattering spectroscopy (RSS), and cross-sectional transmission electron microscopy (XTEM), respectively. The as-implanted results revealed that the LT specimen retains a greater amount of implantation damage than the RT one does due to the occurrence of less in situ annealing in the former during ion implantation. However, the as-annealed results indicated that the shallow junction characteristics of the LT specimens are superior to those of the RT ones when annealing time in FA is greater than 1 h, which is caused by a greater solid phase epitaxial growth (SPEG) rate in the former to anneal out more damage during annealing. Notably, an annealing time of 3 h in FA is needed in order to achieve optimal crystalline recovery and electrical activation in both the one- and two-step post-annealing treatments under investigation. The same holds for both the LT and RT implantations.

1. Introduction

The recent rapid development of innovative micro-electronic devices has sparked growing interest in using ion implantation techniques in forming shallow junctions [1]. Molecular ion implantation has gained much attention due to its exceptional advantages of yielding a lower implantation energy level in boron ions and extracting a higher beam current of the molecular ions from an accelerator [2–4]. Among numerous ion sources, BGe is believed to be one of the most desirable due to the following benefits contributed by the Ge constituent [4–7]: (1) elimination of up to 87% of the incident BGe molecular ion energy thereby greatly lowering the implantation energy in boron ions; (2) enlargement of the extracted BGe molecular ion beam current by a factor of 6.7 when compared to B monomer ion implantation under the same boron energy level thus greatly enhancing the industrial applicability of BGe molecular ion implantation; (3) production of a significant amount of implantation damage thus greatly reducing the channeling of boron atoms; (4) absence of any undesirable physical, chemical, and electrical effects on the silicon target material; and (5) high solubility in the silicon target material.

Notably, in addition to ion implantation techniques, post-annealing treatments are vital in enhancing shallow junction characteristics due to the fact that such treatments are designed to repair implantation damage and to activate implanted ions. Basically, post-annealing treatments are characterized by various annealing methods and a number of annealing steps. The most widely-used post-annealing methods are furnace annealing (FA) and rapid thermal annealing (RTA) methods together with one or two annealing steps [8,9]. The extent of crystalline recovery can be easily probed by obtaining the peak intensity (I_0) of the longitudinal optical (LO) phonon in the crystalline silicon (c-Si) phase of Raman scattering spectroscopy (RSS) spectra [10]. The extent of activation in implanted ions is closely related to junction depth (x_j) and

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http://dx.doi.org/10.1016/j.apsusc.2014.04.099
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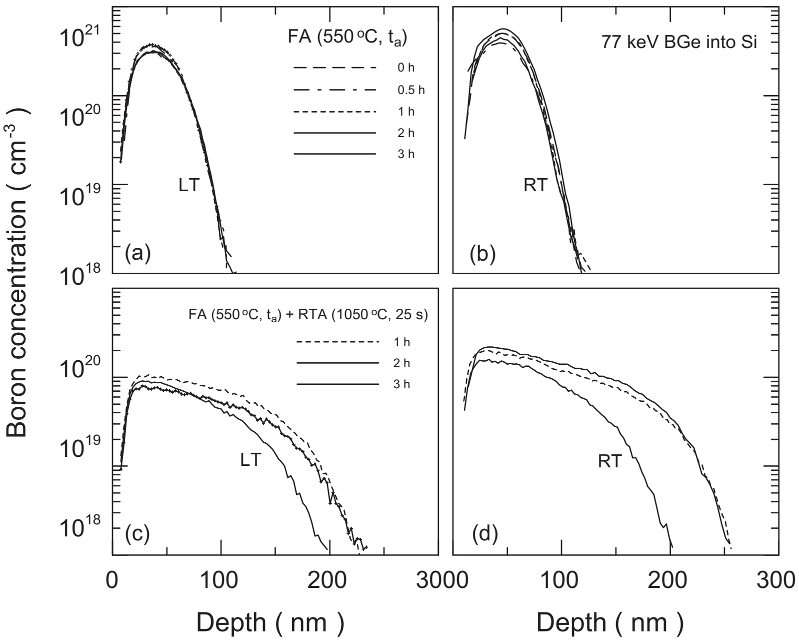

Fig. 1. SIMS-measured depth boron profiles in the as-implanted and as-annealed specimens for the 77 keV BGe implant with an ion fluence of 2×10^{15} cm^{-2} under LT (left) and RT (right) implantations. The post-annealing treatments consisted of one- (top) and two-step (bottom).

sheet resistance (R_s). As a whole, shallow junction characteristics in terms of x_j, R_s, and I_0 play important roles in the development of advanced modern micro-electronic devices. Also, the retention of the amount of implantation damage can be significantly affected by substrate temperature [1,11]. Therefore, it is the central objective of this study to investigate the effects of both one- and two-step post-annealing treatments on x_j, R_s, and I_0 caused by 77 keV BGe molecular ion implantation at liquid nitrogen temperature (LT) and room temperature (RT).

2. Experimental details

This study employed BGe^- molecular ions extracted from the source of negative ions by cesium sputtering (SNICS) on a NEC 9SDH-2 3MV tandem accelerator. Specimens measuring 2 cm × 2 cm in area and 1.5 mm in thickness were carefully prepared from Czochralski-grown phosphorous-doped <1 0 0> silicon wafers (resistivity = 1–10 Ω cm). The specimens were deliberately clamped to a specimen holder in order to ensure good thermal contact when implanting. Notably, the specimens were tilted 7° with respect to the incident ions in order to minimize ion channeling effects. The implantation energy level of the BGe^- molecular ions was 77 keV (the equivalent implantation energy levels for the B and Ge ions separately were 10 and 67 keV, respectively), and the beam current density was kept low to avoid beam overheating. The temperatures were maintained at LT and RT when implanting, in which the LT specimens were cooled by a flux of liquid nitrogen that was passed under the target holder, while the RT ones were not cooled. The implanted area on the specimen was 1.5 cm in diameter. In this study an implantation fluence of 2×10^{15} cm^{-2}, which is much greater than the threshold implantation fluence necessary to cause amorphization ($9.1 \times 10^{13}\ cm^{-2}$) [12] as predicted by the SRIM Monte-Carlo computer code [13], was chosen in order to ensure that an amorphous layer was produced in the specimens. Furthermore, in order to accurately control implantation fluence during the ion implantation experiment, a charge integration measurement taken directly from the specimens was employed. Furthermore, a copper grid was implemented near the target holder in order to reduce any interference from secondary electrons while the measurement was taken.

Following ion implantation, the as-implanted specimens were chemically cleaned before undergoing the FA and RTA post-annealing treatments. In this study, the widely-used one-step (FA) and two-step (FA + RTA) post-annealing treatments were employed. FA was performed in a dry nitrogen ambient at an annealing temperature (T_a) of 550 °C for annealing times (t_a) of 0.5, 1, 2, and 3 h in a Lindberg FA system; while RTA was carried out in a dry nitrogen ambient at a T_a of 1050 °C for a t_a of 25 s in a Heatpulse 610i RTA system. The annealing times of FA involved in the two-step post-annealing treatments were 1, 2, and 3 h.

Following the post-annealing treatments, both the as-implanted and as-annealed specimens were analyzed using secondary ion mass spectrometry (SIMS), resistometry, Raman scattering spectroscopy (RSS), and cross-sectional transmission electron microscopy (XTEM). The SIMS measurements (involving a Cameca IMS4F ion microscope, an 8 keV O_2^+ primary ion beam, and a Daktak 3030 alpha-step profilometer) were used to determine the boron depth profiles of the specimens. The location at which boron concentration (C_B) equals $3 \times 10^{18}\ cm^{-3}$ was adopted herein to determine junction depth x_j [14,15]. The Napson RT-7 four-point probe was utilized to measure sheet resistance R_s. Using a micro-Raman spectrometer, a tripe grating monochromator (TRIAX 550) in backscattering geometry, and an argon laser beam with a single-line wavelength of 514.5 nm, the RSS measurements were made in order to determine the extent of crystalline recovery in the specimens. The scattered light was integrated with a step size of $1.2\ cm^{-1}$ in wavenumber for 90 s. The optical penetration depth (λ_{op}) of the 514.5 nm argon laser beam into silicon materials ranges from 500 to 1000 nm [16–18], depending on the temperature and crystalline status of the silicon materials. Since λ_{op} was greater than the implanted layer under investigation, the resultant RSS detection signals included all the information in the entire implanted layer as well as, to some extent, the bulk silicon. Furthermore, the XTEM measurements (employing FEI Tecnai F20 at an acceleration voltage of 200 kV) were made in order to detect damage microstructures in the specimens.

Please cite this article in press as: J.H. Liang, C.H. Wu, Shallow junction characteristics due to low temperature BGe molecular ion implantation into silicon, Appl. Surf. Sci. (2014), http://dx.doi.org/10.1016/j.apsusc.2014.04.099