Materials Science and Engineering B 159–160 (2009) 361–364

Contents lists available at ScienceDirect

Materials Science and Engineering B

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

Stress-mediated redistribution of Mn in annealed Si:Mn

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ARTICLE INFO

Article history:
Received 22 April 2008
Received in revised form 12 June 2008
Accepted 1 September 2008

Keywords:
Silicon
Manganese
Ion implantation
Annealing
Solid phase epitaxy
Magnetic semiconductor

ABSTRACT

Buried amorphous silicon (a-Si) is produced in Czochralski single crystalline silicon implanted at 340 K with Mn^+ (Si:Mn, $^{55}Mn^+$ doses, $D = 2 \times 10^{15}$ or 1.2×10^{16} cm^{-2}, energy 160 keV). Stress-mediated redistribution of Mn and solid phase epitaxial re-growth (SPER) of a-Si at up to 1273 K (HT), also under hydrostatic Ar pressure up to 1.1 GPa (HP), have been investigated by SIMS, X-ray and related methods. As-implanted Si:Mn indicates magnetic ordering. SPER depends on Mn^+ dosage, HT, HP an on processing time. Processing at 870–1000 K results in a minimum in the Mn concentration at ~0.15 μm depth. At 1170 K and above, the diffusion of Mn to the surface increases with HP. Our results help in understanding the mechanisms of SPER and of origin of magnetic ordering in Mn:Si.

1. Introduction

Ion-beam-induced formation of amorphous silicon (a-Si) and its solid phase epitaxial re-growth (SPER) during annealing of implanted crystalline silicon (c-Si) have attracted interest because of their importance for fabrication of Si devices [1]. SPER of a-Si depends, among others parameters, on temperature (HT) and hydrostatic pressure (HP) [2].

Silicon implanted with Mn^+ at about 620 K and annealed at up to 1170 K has been reported to order magnetically up to 400 K [3,4]. This is important for producing diluted magnetic semiconductors (DMS), of perspective application for spintronics.

Silicon implanted with metallic ions and processed at HT and under HP ≤ 1.1 GPa, indicates interesting properties. Processed Si:V, Si:Cr and Si:Mn show magnetic ordering, confirming DMS features [5–7]. Implantation with Mn^+ at ≤340 K results in partial amorphisation of Si near R_p (projected range of Mn^+). Subjecting Si:Mn to subsequent processing at HT–HP produces magnetically ordered materials [6,7]. In what follows we report new results on the effect of HP applied at annealing on the HT-induced structural changes in Si:Mn, mostly related to SPER of a-Si.

2. Experimental

$^{55}Mn^+$ ions were implanted at 340 K, with doses, $D = 2 \times 10^{15}$ cm^{-2} (ASi:Mn samples) or 1.2×10^{16} cm^{-2} (BSi:Mn) and energy, $E = 160$ keV, into (0 0 1) oriented p-type Czochralski silicon.

The samples were processed, typically for 1 h, in Ar atmosphere at up to 1273 K under HP up to 1.1 GPa. The depth distribution of Mn was determined by Secondary Ions Mass Spectrometry (SIMS, Cameca 6F instrument). X-Ray Reciprocal Space Maps (XRRSMs) were taken using MRD-PHILIPS diffractometer. Magnetic measurements (using SQUID magnetometer) were performed on the as-implanted samples.

3. Results and discussion

Heavy implantation of Si with energetic ions results in a creation of buried a-Si [1]. In the considered Si:Mn samples implantation resulted (TEM results, not presented here) in especially strong structural disturbances at up to 0.25 (±0.05) μm depth, related to the projected range of Mn^+ ($R_p = 0.14$ μm for $E = 160$ keV). As follows from XRRSM measurements (not shown here), as-implanted ASi:Mn exhibits the semi-layered structure composed of less damaged (about 0.05 μm thick) top layer, intermediate strongly damaged region, and the Si substrate practically not disturbed at a depth of about 0.5 μm. Dislocation loops in the {1 1 1} planes with the Burger vector perpendicular to dislocation loops were detected within c-Si in as-implanted Si:Mn.

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doi:10.1016/j.mseb.2008.09.005

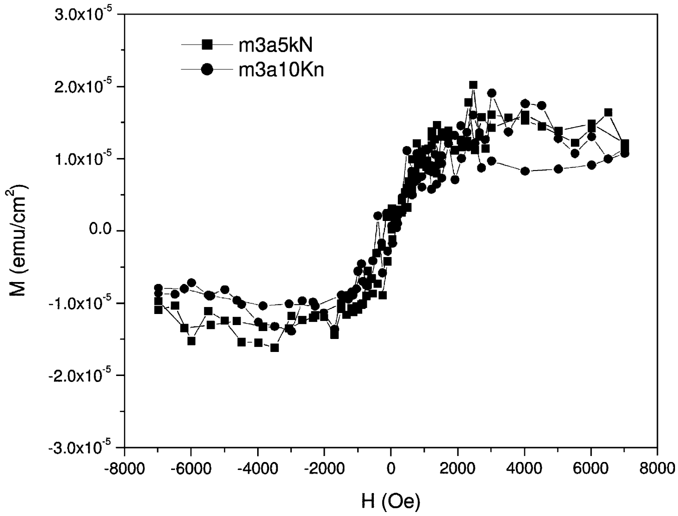

Fig. 1. Magnetisation (M) versus magnetic field (H) measured for BSi:Mn at T = 5 K (■) and 10 K (●). H was applied parallel to sample surface.

The formation of Mn clusters with short range magnetic order has been suggested for as-implanted Si:Mn [8]. Photoluminescence investigation of Si:Mn ($D = 1 \times 10^{16}\,cm^{-2}$) confirmed almost complete amorphisation of the near-surface regions [6].

ASi:Mn prepared by low dose implantation ($D = 2 \times 10^{15}\,cm^{-2}$) presents paramagnetic behaviour. In as-implanted BSi:Mn ($D = 1.2 \times 10^{16}\,cm^{-2}$) magnetic ordering is observed (Fig. 1). Weak dependence of magnetization on temperature suggests magnetic ordering also at above 10 K.

Implanted Mn atoms are mainly located within the a-Si area. The depth distribution of Mn in as-implanted ASi:Mn indicates a broad maximum (Fig. 2), corresponding to R_p. Implantation with $D = 1.2 \times 10^{16}\,cm^{-2}$ leads to almost the same distribution of Mn with a higher peak concentration (Fig. 3).

Distinctly deeper tail of the Mn distribution, especially for the BSi:Mn sample (Fig. 3), may be caused by ion channelling during implantation.

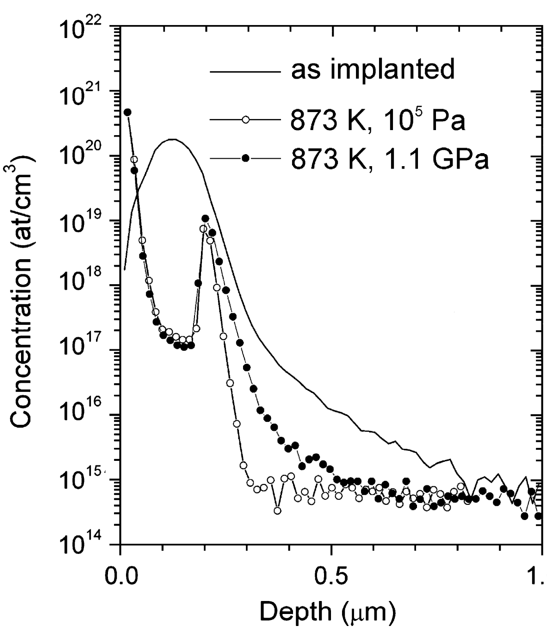

Fig. 2. SIMS depth profiles of ^{55}Mn in ASi:Mn, as-implanted and processed for 1 h at 873 K under 10^5 and 1.1 GPa.

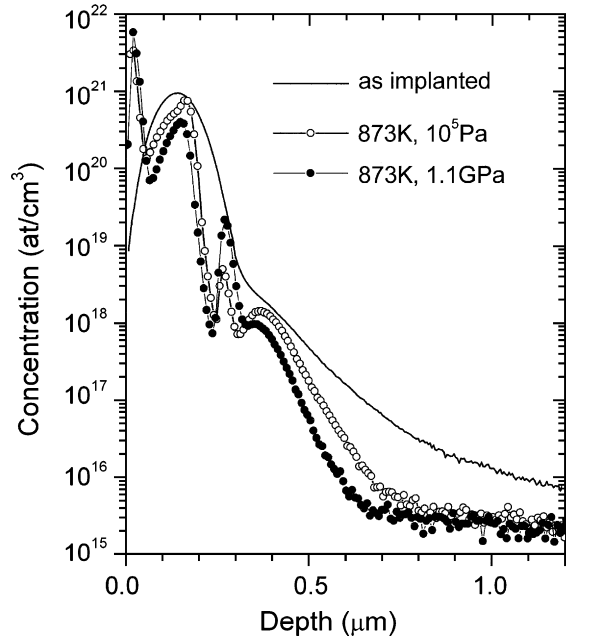

Fig. 3. SIMS depth profiles of ^{55}Mn in BSi:Mn, as-implanted and processed for 1 h at 873 K under 10^5 and 1.1 GPa.

SPER of a-Si and the Mn distribution are strongly dependent on D, HT, HP and on processing time. SPER results in the HT- and t-dependent shift of the a–c interface towards the surface (compare refs. [2,6,7]).

Processing of Si:Mn at ≤670 K for 1 h exerts negligible influence on the shape and position of the Mn concentration profiles [7]; this is obviously related to low mobility of Mn and so to the low SPER rate. As earlier reported [2], also SPER in heavily self-implanted silicon (Si:Si) is minor for the treatments done at 720 K, both under 10^5 Pa and HP. The Si:Si samples are similar in respect of structural damages to presently investigated Si:Mn and so they can be considered as the reference samples.

The depth distribution of implanted Mn atoms in Si:Mn, subsequently processed at 873 K, is strongly dependent on D and, to a lesser extent, on HP (Figs. 2 and 3).

Processing of ASi:Mn ($D = 2 \times 10^{15}\,cm^{-2}$) for 1 h at 873 K, both under 10^5 Pa and 1.1 GPa, results in a maximum Mn concentration at ~220 nm depth below the surface; this concentration exhibits a minimum at ~180 nm depth (Fig. 2), probably related to the a–c interface shifted towards the surface.

About 6 times higher energy introduced into the Si lattice in the case of BSi:Mn samples results in more extended damage affecting SPER. Besides the Mn maximum at about 280 nm depth with the corresponding minimum at ~240 nm depth, of possible origin corresponding to that discussed for the ASi:Mn sample, two other maximum–minimum concentration features are observed (Fig. 3). It is known that chemical interaction of implanted Mn with a-Si can occur in Si:Mn, resulting in a synthesis of some Si–Mn compounds, for example $Mn_{11}Si_{19}$ or Mn_4Si_7 [9]. The peak Mn concentration at ~180 nm and the minimum at ~80 nm depths, both located within the region of the highest Mn concentration in as-implanted BSi:Mn (at the level of $10^{21}\,cm^{-3}$), are probably related to a creation of some manganese silicides.

The weak Mn concentration peak at about 0.4 μm from the surface shows evidence of Mn gettering on implantation-induced defects.

In BSi:Mn, enhanced HP applied at 873 K results in a little faster diffusion of Mn towards the surface at the depths shallower than