Available online at www.sciencedirect.com
ScienceDirect
Thin Solid Films 515 (2007) 8175–8178
www.elsevier.com/locate/tsf

# Carrier control of β-$FeSi_2$ by 1.2 MeV-$Au^{++}$ ion irradiation

Takafumi Jonishi, Yu-ichiro Ando, Akifumi Imai, Yoshihito Maeda *

*Department of Energy Science and Technology, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan*

Available online 20 February 2007

**Abstract**

We have investigated effects of 1.2 MeV-$Au^{++}$ ion irradiation into β-$FeSi_2$ samples which are synthesized by different processes. Such a high energy $Au^{++}$ ion irradiation can be expected to induce Si and Fe vacancies in the β-$FeSi_2$ lattice. After recrystallization of the lattice, we found that one of the samples showed conversion from the initial p-type conduction to the n-type one. RBS analysis revealed that irradiated Au atoms even after recrystallization by thermal annealing were not included in the β-$FeSi_2$ layers. These results suggest that the Au atoms cannot contribute to conversion of the electrical conduction type observed. One possible explanation is that the highly induced Fe vacancy can play donor and its annihilation rate is much slower than that of Si vacancy that surely plays acceptor, so that carrier's compensation balance shifts toward n-type conduction. These results imply that vacancy-induction by high energy ion irradiation can be employed to control a conduction type of β-$FeSi_2$.


*Keywords:* β-$FeSi_2$; Ion irradiation; Ion-beam synthesis; Electrical conduction

## 1. Introduction

There are great interests in Si-based infrared light emitting materials with highly compatible processes for production. Orthorhombic β-$FeSi_2$ consists of non-toxic and abundant elements, and is one of the candidates which are adapted to ecologically friendly semiconductors (i.e. Kankyo semiconductors) [1]. It can be grown directly on/in Si substrates, and emits IR light at 1.55 μm which has been employed in optical telecommunication. However, there remains a problem on difficulties of carrier control of β-$FeSi_2$.

In usual ion-beam synthesis of β-$FeSi_2$ on/in Si substrates, precipitates or thin films with p-type conduction have been obtained [2–5]. The hole concentration was in the range of $10^{18}$–$10^{19}$ $cm^{-3}$. It has been thought that the conduction type and the carrier concentration are dependent upon Fe or Si vacancies in the β-$FeSi_2$ lattice by unintended non-stoichiometry. Suemasu et al. [6] reported that conversion of conduction type was observed by intended variation from stoichiometry of β-$FeSi_2$ thin films. However, the characteristic composition at which the conversion occurred depended on the kind of deposition method. This behavior may be affected by unintended impurities (transition metals) of starting materials employed in the deposition [7]. On the other hand, ion beam synthesis can avoid such an unintended impurity, so that we can investigate effects of vacancies due to composition variation or irradiation related vacancies on the conduction behaviors.

High energy and heavy ion irradiation effects on semiconductor materials have been investigated in order to find vacancy-induced enhancement phenomena.

In this study, in order to find possible carrier control of β-$FeSi_2$ we investigated conduction behavior of β-$FeSi_2$ lattices due to vacancies which are introduced by high energy heavy ion irradiation technology.

## 2. Experiments

Samples were prepared by a mass separated ion beam implantation of $^{56}Fe^{+}$ into ~500 μm thick FZ *n*-Si(001) with 2–8 Ωcm. The multiple ion implantation [2] was carried out at the energies of 100, 80 and 30 keV in this sequence. Its total dose was $1.0\times10^{17}$ $cm^{-2}$. We prepared two samples (Nos. 1 and 2) which were different in their initial conditions. Before 1.2 MeV-$Au^{++}$ ion irradiation, sample No. 1 was annealed at 800 °C for 6 h in an Ar gas ambient in a rapid thermal anneal (RTA) furnace in order to form initial polycrystalline β-$FeSi_2$. 1.2 MeV-$Au^{++}$ ions of dose: $1.5\times10^{15}$ $cm^{-2}$ were irradiated to both samples

* Corresponding author.
*E-mail address:* ymaeda@zenon.energy.kyoto-u.ac.jp (Y. Maeda).

0040-6090/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.tsf.2007.02.044

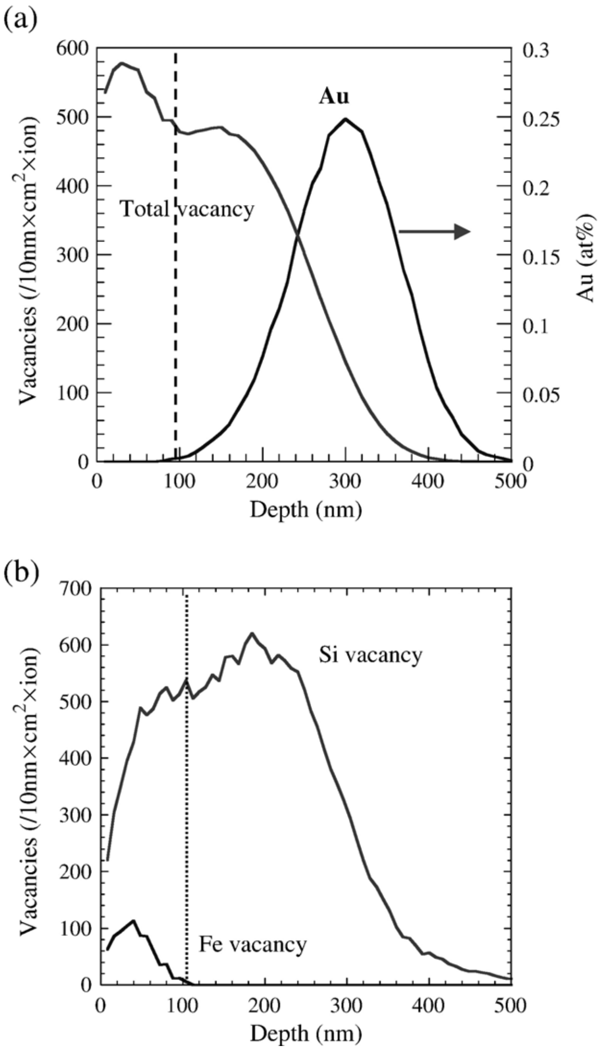


Fig. 1. (a) Depth profiles of vacancy and Au atom calculated by Monte Carlo simulation of SRIM 2003 code. 1.2 MeV-$Au^{++}$ ions were irradiated into β-$FeSi_2$/Si(100). Most of Au atoms can reach deep inside of Si substrate. (b) Fe vacancies can be induced only in β-$FeSi_2$ and Si vacancies in both β-$FeSi_2$ and the Si substrate. The dotted line indicated the depth in which β-$FeSi_2$ forms.

No. 1 (polycrystalline β-$FeSi_2$) and No. 2 (Fe-implanted sample), then both were annealed at 800 °C for 2 h in an Ar gas ambient in an RTA furnace.

The depth profiles of Au and Fe were examined by Rutherford backscattering spectroscopy (RBS). The incident ion of $^4He^+$, the incident energy of 2.0 MeV, the backscattering angle of 165° and the normal incidence of ion beam were employed in RBS measurements. The profiles of implant concentration were determined by SIMNRA simulation. The depth profiles of Si and Fe vacancies induced by $Au^{++}$ ion irradiation were estimated by Monte Carlo simulation of SRIM2003 simulation. The electrical resistance and Hall constant measurements under a 3000 G magnetic filed were carried out by a Van der Pauw method at room temperature. Aluminum films were employed to make an ohmic contact with β-$FeSi_2$.

## 3. Results and discussion

Fig. 1 shows a result of 1.2 MeV-$Au^{++}$ ion irradiation obtained from simulation of distributions of Au and total vacancies by ions and recoils. It shows that we can induce the uniform distribution of vacancies into the β-$FeSi_2$ layer (thickness: 0.06 μm) and that Au atoms are mostly implanted not into β-$FeSi_2$ but into Si before annealing.

The RBS random and aligned spectra of samples No. 1 after $Au^{++}$ ion irradiation (before annealing) revealed that $Au^{++}$ ion irradiated β-$FeSi_2$ had a completely random state. The $\chi_{min}$ of Si was 73% that was much larger than that of 39% in the initial $Fe^+$ ion implantation. The distribution of Au atoms showed mostly a simple Gaussian profile. Also in sample No. 2, we observed the same features.

Fig. 2 shows RBS spectra of samples (a) No. 1 and (b) No. 2 after annealing. In both samples, the redistribution of Au atoms showed the Ostwald ripening phenomenon (separation of profiles) from the simple Gaussian distribution at as-implanted

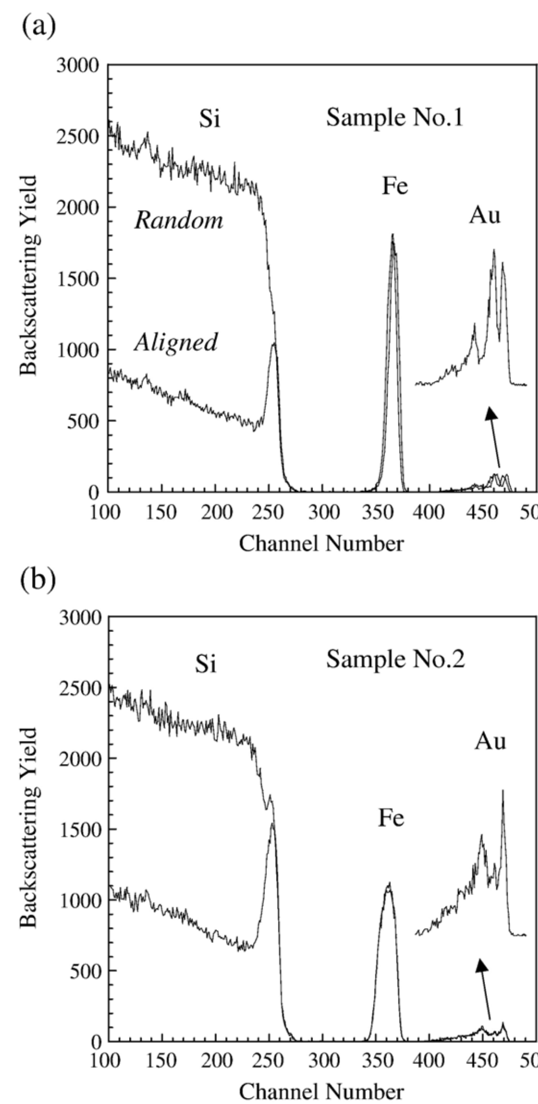


Fig. 2. RBS random and aligned profiles of samples (a) No. 1 and (b) No. 2 which are re-crystallized by annealing at 800 °C for 2 h.