Formation of Light-Emitting Iron Disilicide/Silicon Heterostructures by Means of Pulsed Ion and Laser Beams

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Abstract – Semiconducting iron disilicide (β-FeSi$_2$) is a promising material for the fabrication of Si-based structures emitting light in the 1.5–1.6 μm telecommunication range. In this work β-FeSi$_2$/Si heterostructures were formed by high-fluence implantation of *n*-Si (100) single crystals with iron ions (Fe$^+$) followed by treatments of the implanted Si layers with pulsed laser or ion beams. Structural properties of the obtained heterostructures were studied by X-ray diffraction, transmission electron microscopy and Rutherford backscattering spectrometry. It is shown that pulsed treatment leads to the formation of nanocrystalline FeSi$_2$ layers with a cellular structure and nearly uniform composition. On the base of β-FeSi$_2$/Si layers, light-emitting in the near infrared region p^+–Si/β-FeSi$_2$/n–Si/n^+–Si diode structures were obtained by the implantation of low-energy boron and phosphorous ions.

1. Introduction

The actual problem of modern optoelectronics is the formation of Si-based structures emitting light in the 1.5–1.6 μm telecommunication range at room temperature. One of the approaches to the creation of such structures is the fabrication of continuous and nanocrystalline semiconducting iron disilicide/silicon (β-FeSi$_2$/Si) heterostructures. The main methods for the formation of β-FeSi$_2$/Si heterostructures and light-emitting diodes on its base (ion-beam synthesis and molecular-beam epitaxy) include prolonged (up to 20 h) and high-temperature (up to 950 °C) anneals of Si crystals which are undesirable in the advanced microelectronic technology [1, 2].

An alternative to prolonged thermal anneals can be pulsed nanosecond treatments with high-power laser, electron and ion beams. Due to the short pulse duration (τ<1 μs) and low penetration depth of photons, ions and electrons (d<10 μm) pulsed treatments are not accompanied by the significant heating of whole Si crystal. The treatment of Fe ion implanted Si layers by high-power nanosecond laser or ion beams allowed us to synthesize oriented nanocrystalline β-FeSi$_2$ layers with reduced defectivity and to control the depth distribution of the implanted ions in order to minimize the undesirable diffusion into Si crystal [3–5].

2. Experiment

The β-FeSi$_2$/Si heterostructures were formed by high-fluence implantation of *n*-Si (100) wafers at room temperature with iron ions (Fe$^+$, E=40 keV, Φ=6·10^{16} cm^{-2}). After the implantation Si samples were subjected to the nanosecond treatment with high-power pulsed laser (λ=0.69 μm, λ=80 ns) or ion (C$^+$, H$^+$, E=300 keV, λ=50 ns) beams with energy density in the W=1.2–2.5 J/cm^2 range. The number of pulses (N) varied from 1 to 20. In order to produce shallow p-n junctions, β-FeSi$_2$/Si heterostructures were implanted with low-energy boron ions (B$^+$, E=15 keV, Φ=10^{15} cm^{-2}). Theoretical calculations of the stopping ranges for Fe$^+$ and B$^+$ ions were performed using SRIM code [6].

To improve an electrical contact the backside of *n*-Si (100) wafers was implanted with phosphorous ions (P$^+$, E=25 keV, Φ=10^{15} cm^{-2}). For the electrical activation of the implanted species short-time thermal annealing (T=800 °C, t=20 min) in the N$_2$ ambient was carried out. Structural, electrical and optical properties of the obtained heterostructures were studied by the methods of grazing incidence X-ray diffraction (GIXRD), transmission electron microscopy (TEM), Rutherford backscattering spectrometry (RBS), thermoelectrical probing and electroluminescence (EL) in the near infrared region (1.0–1.6 μm) at the temperatures of 77–300 K.

3. Results and discussion

Pulsed laser annealing (PLA) of the amorphous Si:Fe layers (the thickness of about 100 nm) with the increased energy density (W=2.2 J/cm^2) resulted in creation of the cellular structures (Fig. 1) characteristic for the liquid-phase recrystallization process of the implanted layer containing the low-soluble impurity (iron) [4]. The cells have lateral sizes of about 50 nm and consist of single-crystalline Si.

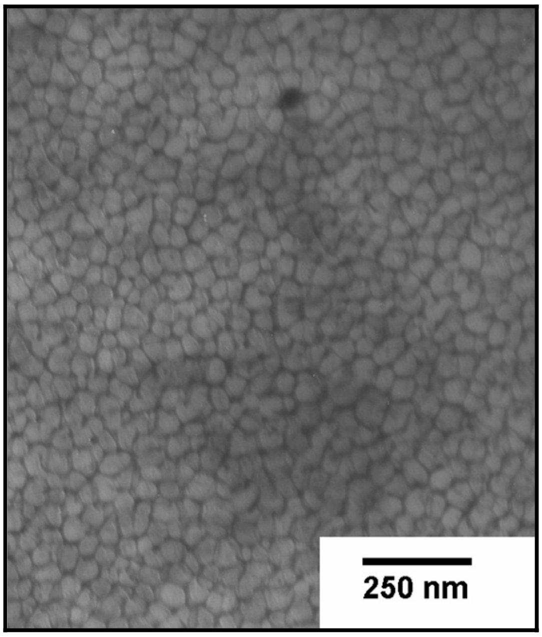

Fig. 1. Bright-field TEM micrograph of the cellular structure of a Si layer after ion implantation (E=40 keV, Φ=6·10^{16} Fe$^+$/cm^2) and PLA (W=2.2 J/cm^2, N=20 pulses)

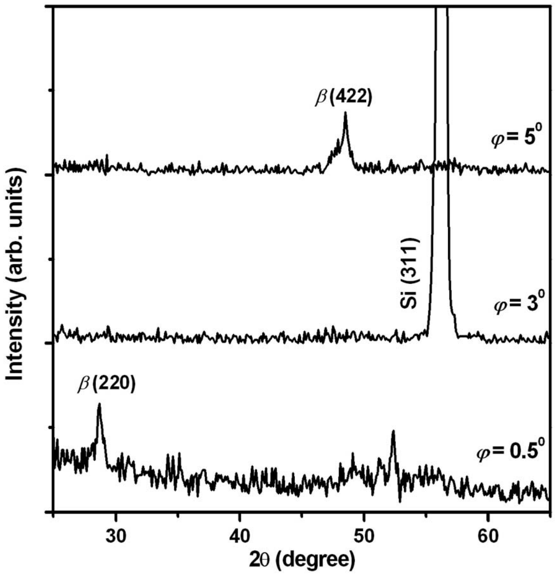

Fig. 2. GIXRD patterns of Si layers after ion implantation (E=40 keV, Φ=6·10^{16} Fe$^+$/cm^2) and PIBT (C$^+$, H$^+$, E=300 keV, τ=50 ns, W=1.5 J/cm^2, N=2) measured at the different angles of incidence (φ=0.5, 3 and 5°)

Iron impurity is located in the cell walls with the thickness of about 10 nm as metastable metallic γ-FeSi$_2$ phase with the single-crystalline structure. For the comparison pulsed ion-beam treatment (PIBT) of the amorphous Si:Fe layers with W=1.5 J/cm^2 energy density resulted in the formation of nanocrystalline β-FeSi$_2$ layer (Fig. 2) with the cells having lateral sizes up to 200 nm and extending into Si up to 150 nm [5]. The difference in the processes of phase formation during PLA and PIBT relates with the various crystallization speeds (V~4–5 m/s and ~1–2 m/s) favoring the formation of γ-FeSi$_2$ or β-FeSi$_2$ phases. Additional short-time thermal annealing (T=800 °C, t=20 min) performed after PLA and PIBT resulted into the phase transformation γ-FeSi$_2$→β-FeSi$_2$ and to the increase of the intensity of β-phase diffraction peaks.

The investigation of Fe atom depth distribution in Si by RBS method showed that when the concentration of Fe atoms in Si layer achieved eutectic level (C_e~10^{22} cm^{-3} or 20 at.%) the movement of the Fe impurity to the surface (segregation) suppressed by the diffusion into Si crystal (Fig. 3). So it seems that used ion fluence (Φ=6·10^{16} Fe/cm^2) is most optimal to suppress undesirable segregation effects. Moreover using of multishot PLA (N=10 and 15 pulses) allowed us to produce β-FeSi$_2$ layers with nearly uniform composition within the thickness of about 100 nm.

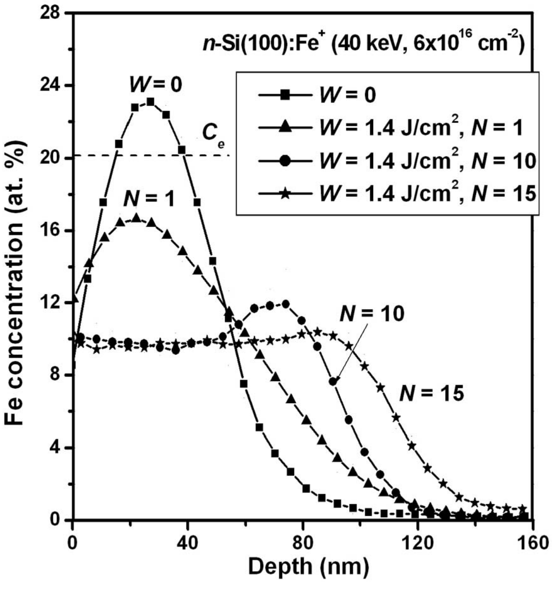

Fig. 3. Depth profiles for Fe atoms in Si obtained from RBS after ion implantation (E=40 keV, Φ=6·10^{16} Fe/cm^2) and PLA (λ=0.69 m, τ=80 ns, W=1.4 J/cm^2) with the different number of pulses (N=1, 10 and 15)

In order to create shallow p-n junction, β-Fe-Si$_2$/n-Si heterostructures were implanted with low-energy B$^+$ ions and thermally annealed to eliminate radiation defects and activate dopants. The investigation of the implanted layers by thermoelectrical probing showed that β-FeSi$_2$ layers had a p-type of conductivity. The comparison of depth profiles for Fe and B atoms in Si obtained theoretically using

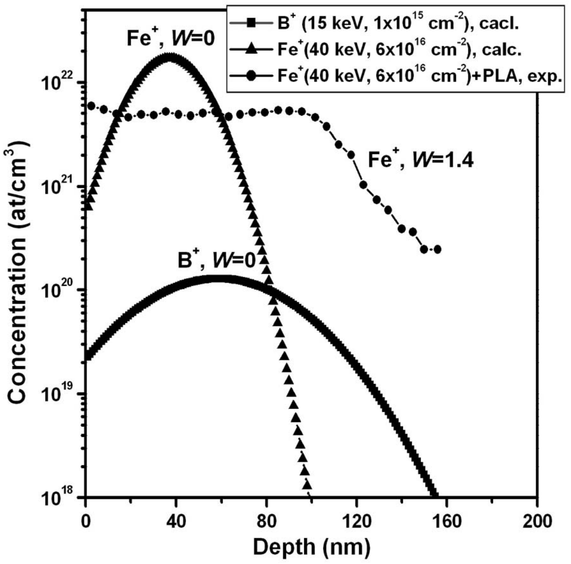

Fig. 4. Depth profiles for Fe and B atoms in Si obtained from the data of SRIM-calculation (W=0) and from the experimental RBS spectra after ion implantation (E=40 keV, Φ=6·10^{16} Fe/cm^2) and PLA (λ=0.69 μm, τ=80 ns, W=1.4 J/cm^2, N=15 pulses)

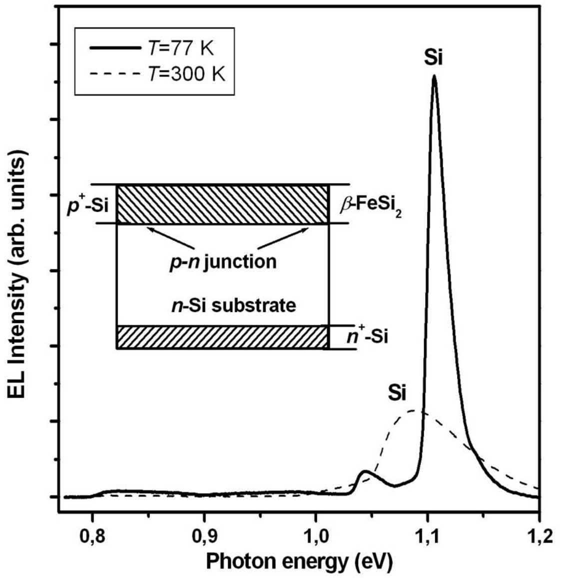

Fig. 5. EL spectra of p^+–Si/β-FeSi$_2$/n–Si/n^+–Si heterostructure measured at T=77 and 300 K. The injection current is 100 mA and the diode area is 1 mm^2. The inset shows schematic image of light-emitting diode

SRIM code [6] and experimentally from RBS data showed its coincidence in tail regions (Fig. 4). This indicates about doping of whole β-FeSi$_2$ layer with the acceptor type impurity and the formation of p-n junction (N_B~10^{18} cm^{-3}) at the depth of about 0.15 μm which is compared with the diffusion length of Fe in Si after PLA.

The obtained heterostructure with p-n junction formed is not optimal from the point of view of effective electrical pumping of the active region of light-emitting diode (β-FeSi$_2$ layer) which have to be located preferably in the n-region of junction [1]. The concentration of Fe atoms at the p-n junction depth is sufficiently low (N_{Fe}~10^{20} cm^{-3}) that leads to the formation of solid solution of Fe in Si rather than the formation of large β-FeSi$_2$ precipitates 10–100 nm in diameter which are the actual sources of light emission in the 1.5–1.6 μm region.

This fact influences directly to the excitation efficiency of the β-FeSi$_2$ layer. Figure 5 shows EL spectra where the signal from Si at 1.1 eV exceeds significantly the signal from the β-FeSi$_2$ layer at 0.8 eV due to the low concentration of Fe impurity in the region of p-n junction where the recombination of the injected carriers takes place. In relation with above mentioned, the further work for the optimization of the synthesis of β-FeSi$_2$ layers and its doping with electrically active dopants is required.

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