Mechanism of Carrier Transport at Low Temperatures in n-Type beta-FeSi2/p-Type Si Heterojunctions Fabricated by Facing-Target Direct-Current Sputtering

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Abstract—The fabrication of n-type β-FeSi2/p-type Si heterojunctions was accomplished by FTDCS at a substrate temperature of 600°C without post-annealing. Their current-voltage characteristic curves were measured at low temperatures ranging from 300 K down to 50 K. In order to examine the mechanism of carrier transport in the heterojunctions using thermionic emission theory, the ideality factor was estimated from the slope of the linear part of forward ln J-V characteristic curves. In the temperature range from 300 K down to 225 K, the ideality factor was 1.23 at 300 K and increased to 2.02 at 225 K. The ideality factor values ≤ 2 implied that the mechanism of carrier transport was governed by a recombination process. In the temperature range from 200 K down to 50 K, the ideality factor was 3.34 at 200 K and increased to 15.56 at 50 K. Parameter A was calculated to be constant. The temperature dependent ideality factor, together with the constant value of parameter A, implied that the predominant mechanism of carrier transport was a trap-assisted multi-step tunneling process. At highly applied forward bias voltage, the mechanism of carrier transport was changed to a space charge limited current process.

Keywords—iron disilicide; FTDCS; heterojunction; I-V characteristic; carrier transport

I. INTRODUCTION

At present, semiconducting iron disilicide (β-FeSi2) is a promising candidate for integration with silicon for optoelectronic applications because of its remarkable electrical and optical properties [1-2]. It possesses a high optical absorption coefficient greater than 105 cm⁻¹ at 1.2 eV and a direct optical band gap of 0.74 eV. The values of band gap correspond to optical fiber telecommunication wave lengths ranging from 1.31 to 1.55 μm [3]. Moreover, β-FeSi2 thin films can be grown epitaxial on Si substrates with small lattice mismatches (2-5%) [3]. It is also an ecologically friendly material because of the non-toxicity of its component elements (Si and Fe) [4].

Previously, the epitaxial growth of β-FeSi2 on Si(111) substrates was realized by facing-target direct-current sputtering (FTDCS) at a substrate temperature of 600 oC without post-annealing [5]. This substrate temperature was 200 oC lower than general post-annealing temperatures. Our β-FeSi2 thin films exhibited n-type conduction with a carrier concentration ranging between 1017 and 1018 cm⁻³. n-Type β-FeSi2/p-type Si heterojunctions that showed good rectifying actions were employed as photodiodes [4]. Then, it was confirmed that their photo detection performances were enhanced at low temperatures [5]. However, their carrier transport mechanism at low temperatures has never been studied. In this study, n-type β-FeSi2/p-type Si heterojunctions were fabricated by FTDCS and their current-voltage (I-V) characteristics were measured at low temperatures ranging from 300 K down to 50 K. Their carrier transport mechanisms were examined using thermionic emission theory. It was demonstrated that a recombination process was the predominant mechanism of carrier transport at temperatures ranging from 300 K down to 225 K and changed to a trap-assisted multi-step tunneling process at temperatures ranging from 200 K down to 50 K. At highly applied forward bias...
voltage, a space charge limited current process was the predominant mechanism of carrier transport.

II EXPERIMENTAL DETAILS

n-Type β-FeSi$_2$ films, with a thickness of 300 nm, were grown epitaxial on p-type Cz-Si(111) substrates at 600 °C by FTDCS using FeSi$_2$ alloy targets (purity: 4N). The substrates were immersed in dilute hydrofluoric acid solution (HF concentration: 1%) in order to remove their native oxide layers and then rinsed in deionized water before being mounted into a FTDCS chamber. The targets and substrates in the FTDCS chamber were separated by a distance of 75 mm and the chamber was evacuated to a base pressure less than $3 \times 10^{-5}$ Pa. During the sputtering process, Ar gas (purity: 6N) was introduced to the chamber at a flow rate of 15 sccm. The sputtering pressure was maintained at a constant $1.33 \times 10^{-1}$ Pa. The plasma DC voltage and current were 1 kV and 1.5 mA, respectively. Using a radiofrequency magnetron sputtering apparatus equipped with a separated load lock exchange chamber, a finger-shaped Pd electrode was deposited on the front Si surface and an Al electrode was deposited on the back β-FeSi$_2$ surface.

The crystalline structure was characterized by XRD (Rigaku, RINT 2000/PC) analysis using Cu-Kα radiation. The I-V characteristics of the hetero junctions were measured in the dark at low temperatures ranging from 300 K down to 50 K using a source meter (Keithley 2400). Using thermionic emission theory, the ideality factor was estimated from the slope of the linear part from the forward lnJ-V characteristic curves.

III RESULTS AND DISCUSSION

Figure I displays the XRD patterns measured in (a) 2θ-θ scan and (b) 2θ scan with an incidence angle of 4° of the β-FeSi$_2$ films. A strong 202/220 peak and a weak 404/440 peak, which were typical XRD peaks of the β-FeSi$_2$ thin films grown epitaxially on Si(111), were observed evidently in the 2θ-θ pattern. The 20 XRD pattern exhibited no peaks. This result implied that polycrystalline β-FeSi$_2$ existed sparingly. Figure 1(c) shows the pole figure concerning β-440/404 peak. This indicated that three types of epitaxial variant were rotated at an angle of 120° with respect to each other [5]. These results confirmed that the β-FeSi$_2$ film was grown epitaxial not just in a direction perpendicular to the film plane, but also in-plane on Si(111) substrate.

Figure II displays the dark reverse and forward J-V characteristic curves measured in the temperature ranging from 300 K to 50 K. The hetero junctions exhibited a good rectifying action with a rectification ratio between the forward and reverse currents at bias voltages of ±1 V of higher than two orders of magnitude. The leakage current was reduced dramatically with a decrease in temperature. This suppression should be attributed predominantly to the reduced carrier density in β-FeSi$_2$ film at low temperatures [2,4].
According to the significant difference in the carrier concentration between our \( \beta \)-FeSi\(_2\) films (\( \sim 1018 \) cm\(^{-3}\)) and Si substrates (\( \sim 1015 \) cm\(^{-3}\)) [5], it can be assumed that the hetero junctions acted almost as a step junction. Therefore, the current flowing through the hetero junctions can be described based on thermionic emission theory as follows [6-7]:

\[
J = J_0 \exp \left( \frac{qV}{nkt} \right) - 1
\]

(1)

Where \( J_0, V, q, k, T, \) and \( n \) are the saturation current density, applied forward bias voltage, unit charge, Boltzmann's constant, absolute temperature and ideality factor. From Eq. (1), the ideality factor was estimated from the slope of the linear part from the forward lnJ-V characteristic curves using the relation:

\[
n = \frac{q}{kT} \frac{dV}{d\ln J}
\]

(2)

Figure 3 displays the temperature dependence of the ideality factor analyzed from the forward lnJ-V characteristic curves. At 300 K, the ideality factor was 1.23 and increased to 2.02 at 225 K. Ideality factor values \( \leq 2 \) implied that the mechanism of carrier transport was governed by a recombination process in the \( \beta \)-FeSi\(_2\) layer and at the hetero junction interface [8]. The defects in the \( \beta \)-FeSi\(_2\) layer might form a deep energy level in the band gap, which could act as a recombination center. At 200 K, the ideality factor was 3.34 and increased to 15.56 at 50 K. Ideality factor values \( >2 \) implied that the tunneling process contributed to the mechanism of carrier transport [8]. This should be attributed to the existence of interface states at the junction interface and the localized electronic states in the \( \beta \)-FeSi\(_2\) layer.

At highly applied forward bias voltage, the lnJ-V characteristic curves became nonlinear. This implied that the predominant mechanism of carrier transport in the hetero junctions was changed to another mechanism, such as space charge limited current process. Based on this process, the relation between current density and applied bias voltage is written as [10]:

\[
\Theta = \frac{qV}{nkt}
\]

(4)

Where parameter \( m \) is a constant greater than 2.

Figure 5 displays the typical forward log J-log V characteristic curves of hetero junctions at 300 K, 200 K and 50 K. At highly applied forward bias voltage, the parameter \( m \) values calculated from the slopes of log J-log V characteristic curves were greater than 2. It was expected that the mechanism of carrier transport in the hetero junctions was governed by a space charge limited current process.
IV SUMMARY

n-Type $\beta$-FeSi$_2$/p-type Si hetero junctions were fabricated by FTDC at a substrate temperature of 600°C. Their I-V characteristics were measured at low temperatures ranging from 300 K down to 50 K in order to examine the mechanism of carrier transport using thermionic emission theory. As temperature decreased from 300 K to 225 K, a recombination process was the dominant mechanism of carrier transport in the hetero junctions. At temperatures below 225 K, the strong temperature dependence of ideality factor, together with the constant value of parameter $A$, implied that a trap-assisted multi-step tunneling process was the dominant mechanism of carrier transport. At highly applied forward bias voltage, the mechanism of carrier transport was changed to a space charge limited current process.

REFERENCES


