Thin Solid Films 557 (2014) 302–306

Contents lists available at ScienceDirect

Thin Solid Films

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

Nitrogen doping effect upon hole tunneling characteristics of Si barriers in $Si_{1-x}Ge_x$/Si resonant tunneling diode

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ARTICLE INFO

Available online 11 September 2013

Keywords:
Thermal nitridation
Chemical vapor deposition
Silicon-germanium alloy
Epitaxial growth
Heterostructure
Resonant tunneling diode
Negative differential conductance

ABSTRACT

Nitrogen atomic-layer (N AL) doping effects upon hole tunneling characteristics of double 4 nm-thick Si barriers in the strained $Si_{1-x}Ge_x$/Si(100) hole resonant tunneling diode (RTD) were investigated. At a Si cap layer on $Si_{1-x}Ge_x$(100) (x = 0.2 and 0.4) formed at 500 °C, it was found that NH_3 reaction was drastically enhanced at 500 °C especially at the Si cap layer thickness less than 0.5 nm, and the fact indicates a possibility of significant intermixing at the Si/$Si_{1-x}Ge_x$ heterointerface. From current–voltage characteristics of the RTDs, drastic current suppression by N AL doping in the Si barriers can be observed with typical degree of current suppression as high as 10^3–10^5 at −10 mV. Moreover, it was found that N AL doping influences, not only upon such current suppression, but slightly upon negative differential conductance characteristics.

1. Introduction

Si-based group-IV-semiconductor quantum-effect devices such as double barrier resonant tunneling diode (RTD) attract interests in the large-scale integration of functional devices for next-generation Si-based large-scale integrated circuits [1]. For example, according to negative differential conductance (NDC) due to quantum mechanical resonant tunneling currents, static random access memory which consists of a single pass transistor and a pair of low-power RTDs is proposed [2]. It could drastically reduce cell space and standby power. Recent progress in strained $Si_{1-x}Ge_x$/Si(100) hole RTD indicates that modulation of energy band structure in the subnanometer-order region, for example, widening band offset at heterointerface of a quantum well and barrier, is important to improve the device performance at higher temperatures far from cryogenic temperatures [3,4]. However, there are some serious issues about effective suppression of strain relaxation and intermixing at a heterointerface of $Si_{1-x}Ge_x$/Si especially at high Ge fraction which is formed by low-temperature thermal chemical vapor deposition (CVD). In our previous work on epitaxial growth of N atomic-layer (AL) doped Si(100) [5], it has been found that a small part of N atoms is ionized as a donor at higher temperatures than around 100–125 K. If the N AL doping technique is utilized especially in the ultrathin Si tunneling barrier layer, enhancement of an effective barrier height is expected by local Coulomb potential generation as well as an increase of bandgap (e.g. ultrathin film formation with Si nitride). Therefore, in this work, in order to overcome the above undesired negative effect by increasing band offset and by improving resonant-tunneling characteristics, we examined effectiveness of N AL doping in Si tunneling barrier layer of RTD.

2. Experimental details

Schematics of top and cross-sectional views of the fabricated RTDs are shown in Fig. 1. Strained $Si_{1-x}Ge_x$/Si(100) heterostructure with/without N AL doping in double Si barriers were fabricated by using an ultraclean hot-wall low-pressure CVD (LPCVD) system [6] with a SiH_4-GeH_4-H_2 gas mixture and N AL doping at a typical temperature of 500 °C, subsequently after formation of p^+ $Si_{0.8}Ge_{0.2}$ (5 nm)/p^+ Si (400 nm)/Si (100 nm)/p Si(100). Before loading into the LPCVD, Si(100) substrates (1–5 Ωcm) were cleaned with a 4:1 solution of 96% H_2SO_4 and 30% H_2O_2 for several times and rinsed with high-purity deionized (DI) water. Then, they were dipped into a 2% diluted HF solution for 30 s in order to remove native oxide and rinsed with DI water for 3 min. Structural parameters for the undoped region are the same as described in Ref. 3. Ge fraction of $Si_{1-x}Ge_x$ layers is x = 0.2 or 0.4 and the total thickness of $Si_{1-x}Ge_x$ is estimated within its critical thickness [7]. For each Si barrier layer, thickness is 4 nm and N atom density (dose amount) was 2.4×10^{14} or 1.3×10^{14} cm^{-2} (0.35 or 0.19 AL; 1 AL on Si(100) = 6.8×10^{14} cm^{-2}). Here, N atom density was chosen from the range in which crystallinity degradation is negligibly small [8].

Current (I)–voltage (V) characteristics of N AL doped RTDs were measured at various temperatures of 10–300 K. Then, in order to evaluate effective barrier height at negligibly small electric field, the Richardson–Dushman plots [9] were examined under an assumption that the current

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http://dx.doi.org/10.1016/j.tsf.2013.08.124

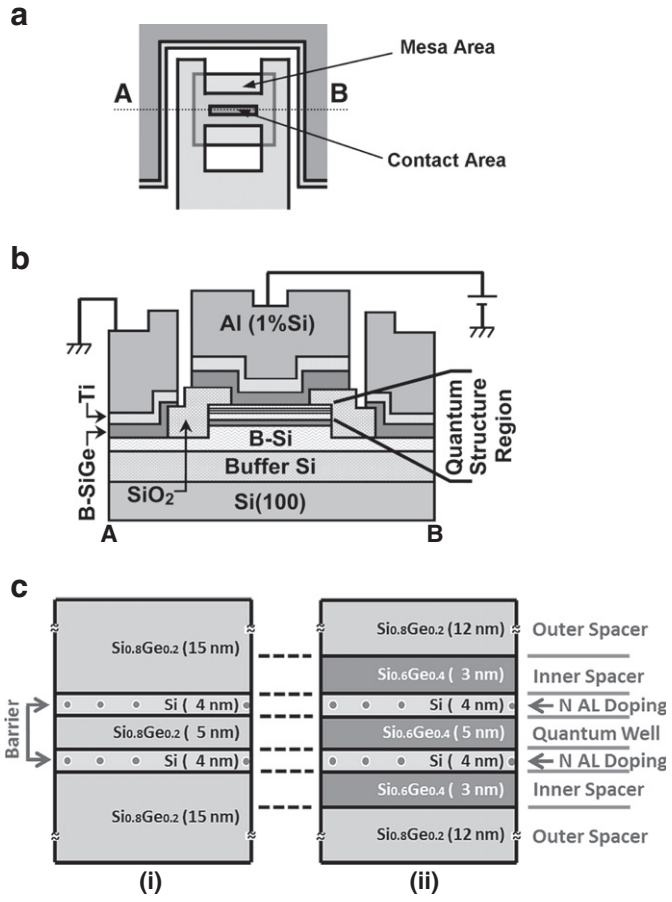

Fig. 1. (a) Top view (mesa area: 100 um^2, contact area: 60 um^2), (b) cross-sectional view and (c) schematics of undoped resonant tunneling structure region in N AL doped RTD. Ge fraction for quantum well and inner spacer is (i) 0.2 and (ii) 0.4.

is considered as non-resonance thermionic emission. Here, the Richardson–Dushman equation is known as

$$J_{\mathrm{th}} = AT^2 \exp[-\Phi/(k_{\mathrm{B}}T)], \tag{1}$$

where J_{th} for thermionic emission current density, A for Richardson's constant, T for temperature, k_{B} for Boltzmann constant, and Φ for effective barrier height. Thus, effective barrier height could be derived as

$$\ln\left(J_{\mathrm{th}}/T^2\right) = -\Phi/(k_{\mathrm{B}}T) + \ln(A). \tag{2}$$

This equation means that an effective barrier height could be estimated by gradient in $\ln(J_{\mathrm{th}}/T^2)$ vs $(-1/T)$ plot. Moreover, in order to evaluate symmetricity of barrier structure, the Fowler–Nordheim plots [10] at low temperature of 10 K were examined. Here, we ignore image-force barrier height lowering. Accordingly, the Fowler–Nordheim emission current density would be expressed as

$$J_{\mathrm{fn}} = \left(q^3/8\pi h\Phi\right) F^2 \exp\left[-8\pi(2m)^{1/2}\Phi^{3/2}/3hqF\right], \tag{3}$$

where J_{fn} for Fowler–Nordheim emission current density, q for electronic charge, h for Planck's constant, F for electric field, and Φ for effective barrier height. Especially, we determined F by applied voltage divided by the sum of the thicknesses for two Si tunneling barriers, a quantum well and a spacer. Similar to the case of the Richardson–Dushman equation, $\ln(J_{\mathrm{fn}}/F^2)$ vs $(-1/F)$ plot would show a straight line describing the barrier height.

3. Results and discussion

3.1. Suppression of enhanced NH_3 reaction due to intermixing at the Si/$Si_{1-x}Ge_x$(100) heterointerface

If intermixing occurs at the Si/$Si_{1-x}Ge_x$(100) heterointerface, it is expected that chemical bonds of Ge–N tends to be formed in the Si tunneling barriers as well as Si–N. Especially in the present work, we chose to investigate pure influence of Si–N formation in two Si tunneling barriers. For the purpose, in order to determine effective minimum thickness for Si cap layer on $Si_{1-x}Ge_x$/Si(100) (x = 0.2 or 0.4) formed at 500 °C, N atom amount from thermal NH_3 decomposition was investigated. Thermal nitridation was performed at 500 °C and NH_3 pressure of 1.9 Pa for 30 s. Surface N atom amount was evaluated by X-ray photoelectron spectroscopy. Fig. 2 shows dependence of surface N atom amount on Si cap layer thickness on strained $Si_{1-x}Ge_x$(100). It was found that NH_3 reaction was drastically enhanced at 500 °C especially at the Si cap layer thickness which is less than 0.5 nm (3 ~ 4 AL thickness of Si atom), and the fact indicates a possibility of significant intermixing at the Si/$Si_{1-x}Ge_x$ heterointerface which will cause the enhanced NH_3 reaction due to the existence of segregated Ge atoms at the topmost surface. Therefore, we set an N AL doped region in the middle position of each layer (i.e. Si(2 nm)/N/Si(2 nm)) for a symmetric structure and negligibly small Ge segregation at the N doped position. Because most of N atoms are considered to exist at most around a few AL depth from the surface [11], it could be considered that Ge segregation occurs in about 0.5 nm-thick region in the Si cap layer. This means that an effective Si barrier thickness becomes smaller and abruptness of heterointerface is degraded, this will possibly influence upon hole resonant characteristics. Therefore, lowering the epitaxial growth temperature will be important for the higher-performance hole RTD. Finally, a 2 nm-thick Si cap layer was formed on $Si_{1-x}Ge_x$(100) in order to avoid influence of segregated Ge atoms in the fabricated hole RTDs.

3.2. Temperature dependence of current–voltage characteristics of RTDs

I–V characteristics of N AL doped RTDs measured at 10 to 300 K are shown in Fig. 3 ($Si_{0.8}Ge_{0.2}$/Si RTD) and Fig. 4 ($Si_{0.6}Ge_{0.4}$/Si RTD). Symmetric I–V curves with clear NDC at low temperatures were observed

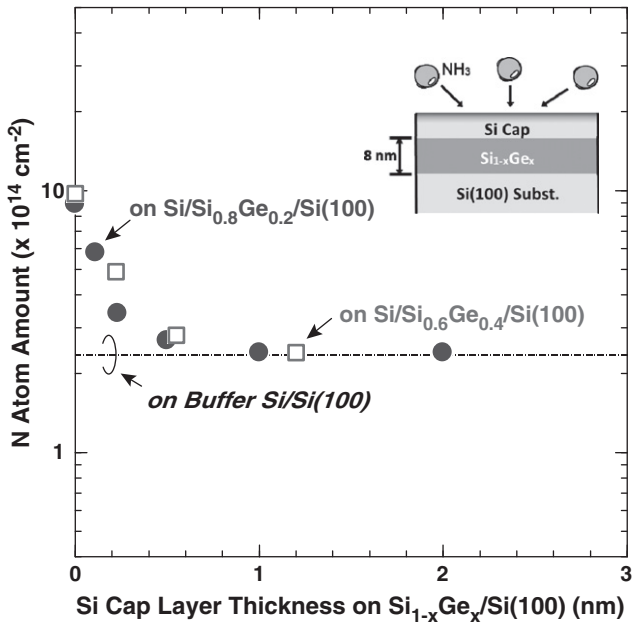

Fig. 2. Si cap layer thickness dependence of N atom amount after thermal nitridation on Si/$Si_{1-x}Ge_x$(100) (x = 0.2, 0.4) at 500 °C.