Investigation of In-situ Doping Profile for N+/P/N+ Bidirectional Switching Device using Si_{1-x}Ge_x/Si/Si_{1-x}Ge_x Structure

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ABSTRACT

In this research, we proposed steep and uniform doping profile of N+/P/N+ multilayer for bidirectional two-terminal switching diode based on Si_{1-x}Ge_x alloy. In strained Si_{1-x}Ge_x alloy, the phosphorus doping profile is more stable because it has higher incorporation rate of phosphorus compared with the unstrained silicon. Thus, we obtained the N+/P/N+ junction doping profile with N+ doping ( > 1 \times 10^{20}) and P doping ( < 2 \times 10^{19}) concentration and could observe the bidirectional current flow.

This research lies in founding fundamental researches for realizing bidirectional two-terminal switching device of Spin-Transfer-Torque Magnetic Random Access Memory (STT-MRAM) that can possible improve current density by controlling length of the P-type layer and doping profile by using an optimized process parameter.

KEYWORDS

Switching device, Doping profile, UHV-CVD, SiGe, NPN, STT-MRAM.

1 INTRODUCTION

STT-MRAM is a Magnetoresistive Random Access Memory (MRAM) based on Spin-Transfer-Torque (STT) switching, which has been researched widely for a long time due to its good scalability, low manufacturing cost, and fast operation [1-2]. The conventional MRAM with bypass line structure uses a magnetic field to switch the MTJ and the magnetic field must increase proportionally to the size of the MTJ, which cause an issue in scalability. STT-MRAM has advantage of better scalability because of different writing mechanism which determines the direction of current status of MTJ on the basis of the spin polarization [3]. However, STT-MRAM is still larger than select device for resistive RAM (RRAM) or phase change RAM (PRAM) because of three terminal MOSFET structure. And, it has critical issues for further cell size scaling such as area penalty and performance degradation by Short Channel Effect (SCE).

In order to solve these issues, various two-terminal switching devices have been developed to replace MOSFET selector. For using a select device of STT-MRAM, it needs higher electrical properties than on-current (2MA/cm^2 at 3V) and on/off ratio (10^3) at least. Poly-Si N+/P/N+ diode with lower current density due to high resistance and Metal-Insulator-Metal (MIM) and Metal-Silicon-Metal (MSM) diode with lower on/off ratio are difficult to use as a select device. Otherwise, Epitaxial Si_{1-x}C_x N+/P/N+ diode the highest candidate of select device with steep doping profile, could obtain high enough on/off ratio. Nevertheless, it also still has weakness in declining current density because a number of dislocations are generated due to large mismatch of \sim 35 \% between silicon and carbon [3-6].
Therefore, we propose the strained Si$_{0.8}$Ge$_{0.2}$ (N+) / Si (P) / Si$_{0.8}$Ge$_{0.2}$ (N+) epitaxial structure on Si substrate as a figure 1. This strained structure has low dislocation of 4.5% from silicon substrate and ability to get the flat and steep doping profile in N+/P/N+ layer because it has higher incorporation rate of phosphorus compared with the unstrained silicon [7]. Furthermore, at the interface of Si/Si$_{1-x}$Ge$_x$ heterojunction, the strain induced splitting and shift of the conduction band can easily lead to the high density of electron on the degenerate sub-band.

2 EXPERIMENTS AND DISCUSSION

The standard Si wafer was prepared with RCA (SC-1 and SC-2) pre-cleaning. The standard cleaning solution #1 was used for removing organic contaminants from the surface of the bare wafer at first. It consists of a mixture of ammonium hydroxide (NH$_4$OH), hydrogen peroxide (H$_2$O$_2$), and DI water (H$_2$O). A concentration ratio for the solution is 0.05:1:5. The second cleaning process was conducted for removing some metallic contaminants from the wafer surface with standard cleaning solution #2. It consists of a mixture of hydrochloric acid (HCl), hydrogen peroxide (H$_2$O$_2$), and DI water (H$_2$O) and concentration ratio is 1:1:5. After the cleaning process, N-type and P-type layers for epitaxial N+/P/N+ multilayer were grown on P-type silicon (100) substrate for the split doping test in a Ultra High Vacuum Chemical Vapor Deposition (UHV-CVD, EUREKA 2000) system.

The reactant gases were introduced through welded stainless-steel pipes with the flow rates precisely controlled by mass flow controllers (MFC). Ar (1000 sccm), Si$_2$H$_6$ (50 sccm), GeH$_4$ (100 sccm), CH$_3$SiH$_3$ (50 sccm), 0.5% of B$_2$H$_6$/He (300 sccm), 0.5% of PH$_3$/He (300 sccm), H$_2$ (1000 sccm), SF$_6$ (100 sccm) and Cl$_2$ (10 sccm) are available.

To avoid contamination of the reaction chamber, the chamber were first evacuated and purified by Ar (200 sccm) before being filled with reactant gases. Disilane (Si$_2$H$_6$) is used as silicon source and dilute germane (GeH$_4$ in H$_2$) is used as germanium source. B$_2$H$_6$ and PH$_3$ are used as P-type and N-type dopants, respectively.

The reaction chamber was heated by the silicon carbide resistance heater for maintenance and stability. Before quantum well growth the reaction chamber was maintained at the base temperature ~ 600 °C to minimize background impurity level. The base pressure was below 1 × 10$^{-7}$ (Torr) and the working pressure range is 1 ~ 5 mTorr with Si$_2$H$_6$ (80 %) and GeH$_4$ (20 %).

We grow the N-type epitaxial silicon layer with phosphorus. The flow rate was split as PH$_3$ (100 sccm, 200 sccm, 300 sccm) in order to confirm doping level by gas density and growth time was 7 minutes at 700 °C.

To grow N-type layer, we applied in-situ doping technique. It is more effective than ion implantation technique. Although it can obtain high doping concentration, implantation lead to Transient Enhanced Diffusion (TED) hindering formation the steep doping profile and losing dose of phosphorus. By applying in-situ doping, any ion implantation damage and deep diffusion can be avoided and the high phosphorus concentration and steep doping profile can be achieved [8].
The Phosphorus doping concentration is $7 \times 10^{19}$ atoms/cm$^3$ and no uniform doping profile at epitaxial growth of Si (40 nm) layer. The figure 2 shows a typical doping profile concentration in epitaxial silicon layer without any growth interruption. It was measured to detect Si and Phosphorus ions by secondary ion mass spectroscopy (SIMS) in condition of Cs+ ion Gun, impact energy (15 Kev), current (30 nA), and raster size (200 μm × 200 μm). The SIMS measurement system has some error margins in the depth and concentration scales. In this figure, we could see quite high doping concentration in silicon, $7 \times 10^{19}$ atoms/cm$^3$ but could not see uniform doping profile because of vacancy diffusion in single crystal. Therefore, we use the strained structure as SiGe instead of Silicon in order to obtain the uniform doping profile. The reason why phosphorus doping is conducted more stably in SiGe structure than silicon can be illustrated with the following reasons.

There are four kinetic functions: 1) Desorption from the silicon surface into the gas phase, 2) adsorption from the gas phase onto the silicon surface, 3) incorporation from the surface into the solid, and 4) segregation from the solid back onto the surface. We know that no desorption and segregation from the substrate occurs back to the surface at lower temperature than 800 °C [9, 10]. Therefore, we can describe the incorporation and adsorption as function of material and growth conditions. The stronger phosphorus gas is absorbed onto surface of silicon or silicon germanium, the higher amount of the surface concentration could be gained. We assume carefully that the surface doping concentration on the Si is higher than SiGe. This means that the function of incorporation from the SiGe surface into the solid is stronger compared with the silicon layer. The larger the incorporation rate the more dopant is sited, less level of phosphorus segregation, and the steeper the rise or decay of the phosphorus profile [7].

In addition, the growth temperature of below 600 °C is better because the atoms vibrate strongly at high temperatures. The diffusion factor is large in high growth temperature. In homogeneous material, there is a barrier to diffusion created by neighboring atoms that need to move randomly to let the diffusing atom pass. Thus, atomic vibrations created by temperature assist diffusion. The effect of temperature in diffusion is given by an intrinsic diffusivity (Di) equation (1).

$$D_i = D_0 e^{-E_a/KT}$$ (1)

Where $E_a$ is the activation energy of the natural vacancy, $D_0$ is the maximum diffusion coefficient, $k$ is the Boltzmann constant, and $T$ is the temperature in units [11].

With theories above, it was confirmed that stable doping is possible in SiGe. We fabricated the N+/P/N+ multilayer using SiGe material. At first, N-type layer was grown epitaxially using SiGe material with a phosphorus dopant in state of PH$_3$ (200 sccm) flow rate for 4500 second at 600 °C.
Figure 3. This figure shows the effect of in-situ doping with phosphorous and boron according to prior art UHV-CVD reaction. (a) The uniformly doped concentration of phosphorus is $10^{20}$ atoms/cm$^3$ on $\text{Si}_{0.8}\text{Ge}_{0.2}$ (40 nm) layer. (b) The uniformly doped doping concentration of boron is $10^{19}$ atoms/cm$^3$ on strained Si (40 nm) layer.

As in figure 3 (a), the experiment on N-type layer resulted in producing P doping concentration at $10^{20}$ atoms/cm$^3$ that was doped uniformly at $\text{Si}_{0.8}\text{Ge}_{0.2}$ (40 nm). After N-type layer test, the in-situ doping test for P-type layer was conducted. The P-type Si layer was epitaxially deposited on Si substrate using $\text{Si}_2\text{H}_6$ (15 sccm) and $\text{B}_2\text{H}_6$ (5 sccm) flow rate for 1 hour at the 600 °C.

In our sandwiched structure as a figure 1, the silicon layer is the most proper for P-type layer because the most stable material composition rate of $\text{Si}_{0.8}\text{Ge}_{0.2}$ is lower than 100 nm and thicker thickness may cause dislocation due to lattice mismatch between Si and Ge [12, 13]. Lattice constant of germanium (5.657 Å) is larger than that of silicon (5.431 Å). The SiGe and Si layers combined with relation to compress and tensile strain because the strained layer has low binding energy near the local dislocation. Figure 3 (b) shows the result of that steep and stable boron doping profile can be obtained easily at epitaxial growth of Si (40 nm).

Figure 4. This figure shows the experiment result for N+/P/N+ bidirectional switching diode. Doping profile density is $7\times10^{19}$ / $2\times10^{19}$ / $2\times10^{20}$ in an N+ (33 nm) / P (50 nm) / N+ (130 nm) layer respectively.

After checking the in-situ doping tests, the main process of N+/P/N+ multi-layer structure is realized in the same process condition. In order to obtain proper p-region, we had enough time to reduce the phosphorus diffusion to a second P-layer by eliminating remaining P-dopant gas. And the middle layer thickness is deliberately considered 100 nm. Figure 4 indicates the SIMS result of the main process, which tells the obtainment of the same doping profile with previous two tests on the bulk silicon. N-type layer has a higher doping level than P-type layer by an about $10^1$ atoms/cm$^3$ and has the length of P-type layer in the middle approximately 50 nm.
After the doping experiment, the N+P/N+ junction device with an area of $6 \times 6 \ \mu m^2$ was fabricated by photolithography. The patterned photoresistor was used as a hard mask, and the SiGe and Si layers were etched by reactive ion etching (RIE). PECVD SiO$_2$ (50 nm) was deposited for isolation. Via hole is patterned (via pattern $4 \times 4 \ \mu m^2$) by photolithography and etched followed by SiO$_2$ RIE. The metal contact (Au / Ti: 100 nm / 50 nm) was fabricated by the lift-off technique and then measure the I-V characteristics of this diode using Agilent/HP 8110A Pulse Generation.

Figure 5 shows the result of I-V measurement with applied voltage (-4V ~ 4V). Figure 5 (a) is log scale and (b) is linearly scaled to illustrate the on current density and on/off ratio. From the results, the bidirectional current flow was confirmed. However, we found a low on-current of about 0.1 MA/cm$^2$ at 3V and a low $I_{on} / I_{off}$ ratio of 10 ~ 100 under an operational voltage range of 0.5 ~ 3V. Nevertheless, the significance of this study lies in founding fundamental researches for optimization of the process parameter such as temperature, material composition ratio, gas concentration, and growth time. The research of bidirectional switching device is possible to alternative choice for select device of STT-MRAM.

3 CONCLUSION

An N+/P/N+ SiGe heterojunction device has been researched elucidate the optimal doping conditions for better device characteristic based on epitaxial growth. In this paper, we investigated the influence of the phosphorus doping for materials and conditions such as temperature, growth time and gas concentration. We optimized condition (based on Si$_{0.8}$Ge$_{0.2}$, B$_3$H$_6$: 5 sccm, PH$_3$: 200 sccm, time: 450 / 3600 / 4500 sec, temperature: 600 °C) with 50 nm of P junction length for a two-terminal switching device of scalable STT-MRAM. From this experiment result, it is expected that a bidirectional N+/P/N+ SiGe heterojunction structure can be one of the solutions for a switching device in STT-MRAM.

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