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Improvement of Interface Properties of Ge-MISFET with Crystalline La_2O_3 high-*k*/Ge(111) Gate Stacks by Wet Treatments

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Abstract

We have demonstrated that the interface state density between epitaxially grown high-*k* La_2O_3 gate insulator and germanium (Ge) without any passivation layers can be reduced by dipping Ge substrates into the I_2 solution of low concentration before the growth. This treatment shows enough stability for the preparation of Ge-MISFETs by using Lu-doped La_2O_3/La_2O_3/Ge stacked structure, and their electrical properties such as the sub-threshold swing which relates to the interface state density are improved in comparison with the conventional sulfur treatment.

1. Introduction

Germanium (Ge) has been considered as the promising candidate channel material because of its high electron and highest hole mobility, and the gate stack between high-*k* and Ge without any low permittivity interfacial layer is desirable for future miniaturization. We have demonstrated low interface defects between the crystalline La_2O_3 high-*k* gate insulator and Ge(111) by using the atomic-arrangement matching condition at a low growth temperature [Figs. 1(a) and (b)] [1]. Moreover, we have achieved a significant reduction of *C-V* hysteresis width by using crystalline Lu-doped La_2O_3 capping layers [Fig. 1(c)], and the sufficient stability have been achieved for the preparation of Ge-MISFETs [2]. However, a surface state and roughness much affect their interface properties [Figs. 1(d) and (e)], and the interface state density (D_{it}) is $\sim 10^{12}$ cm^{-2}eV^{-1}.

Fluorine or sulfur treatment methods are reported to improve the interface property [3, 4]. Moreover, the passivation of Ge substrates with hydrogen halide solutions is also reported and the passivation robustness for growth of native oxide increases from HF, HCl, HBr to HI [5]. However, passivation effects on the interface of the epitaxially grown high-*k* on Ge are rarely reported unlike gate stacks with the interfacial layer such as GeO_2.

In this report, passivation effects on Ge surfaces before the growth of crystalline La_2O_3 are characterized by using several wet treatments from a viewpoint of reduction of the D_{it}.

2. Experimental

La_2O_3 and Lu-doped La_2O_3 capping layers were grown by pulsed laser deposition (PLD) successively on a p-Ge(111) substrate at 350°C in a vacuum chamber where an energy density is about 1 J/cm^2 at 1 Hz. Typical film thickness is about 8 nm in each layer. Native oxides were removed from the Ge surface by dipping in a HF (1%) solution and a HCl (12%) solution, followed by rinsing the surface in deionized water (DIW). The surface wet treatments were done by dipping the Ge substrates in $(NH_4)_2S_x$ (5–8 % S), I_2 (0.5 or 0.005 mol/L) and H_2O:H_2O_2:NH_4OH (dilute SC-1) solutions for 3 to 20 min. The interface state densities were evaluated by the conductance method measured at room temperature [6, 7]. Many top electrodes were formed on a substrate (about 5 x 10 mm rectangular) and several randomly selected points were measured in the case of MIS samples.

The Ge-MISFETs with the crystalline La_2O_3 gate stacks were prepared. The source and drain (S/D) regions were formed by thermal diffusion of phosphorus (P) from a solid diffusion source [8, 9]. After the S/D formation, the crystalline La_2O_3 and Lu-doped La_2O_3 layers were grown at 350°C. Au and AuSb thin films as the gate and S/D contact electrodes were formed by thermal evaporation and were patterned.

3. Results and Discussion

Figure 2 shows the D_{it} under the flat band condition of the Au/Lu-doped La_2O_3/La_2O_3/Ge MIS structure treated in the various solutions. The D_{it} of the samples dipped in I_2 solution is $\sim 5 \times 10^{11}$ cm^{-2}eV^{-1} and is almost half of the conventional sulfur treatment. Moreover, the treatment by 0.005 mol/L I_2 solution (low iodine concentration) is better than that by 0.5 mol/L (high iodine concentration), since scattering is seen in the latter. A similar tendency is observed in the *J-V* characteristics, and the leakage current at $V_g = -1.0$ V of the sample treated by the solution of low iodine concentration is less than 10^{-6} A/cm^2.

It is well known that Ge can be etched by dipping into oxidant solutions, and we observed the surface roughness of the Ge substrate before and after treatments by AFM. These results show that the RMS roughness of the sample treated in the low iodine concentration is smaller than that in the high iodine concentration or the conventional sulfur treatment. Moreover, Fig. 3 shows the I *3d* XPS spectra of the Ge substrate treated by the I_2 solution. Iodine peaks are clearly observed and this indicates that iodine remains on the surface. From these results, the reduction of D_{it} is induced by a small surface roughness and iodine termination.

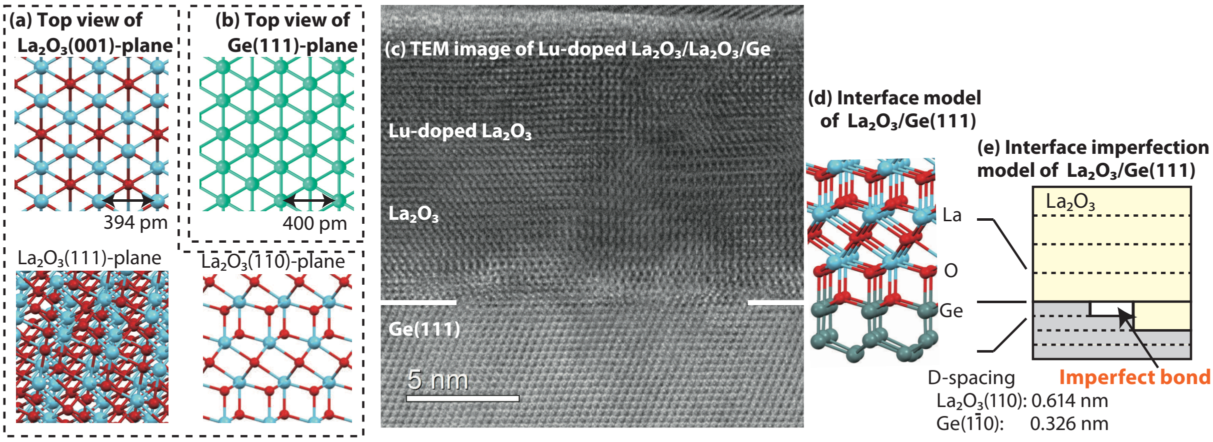

Fig.1 Atomic arrangements of (a) La_2O_3(001), (111) and (110), and (b) Ge(111). Red, blue and green circles indicate O, La and Ge atoms, respectively. (c) HR-TEM image of Lu-doped La_2O_3/La_2O_3/Ge, and the models of (d) its interface and (e) interface imperfection [1,2].

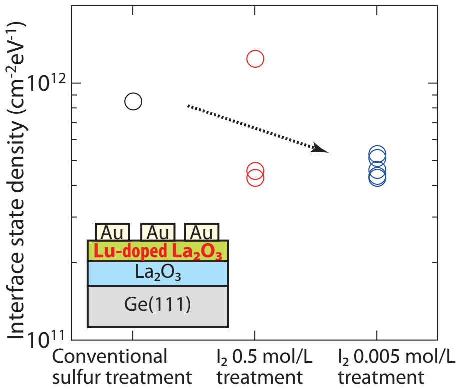

Fig.2 D_{it} of the Au/Lu-doped La_2O_3/La_2O_3/Ge MIS structure treated by the various solutions.

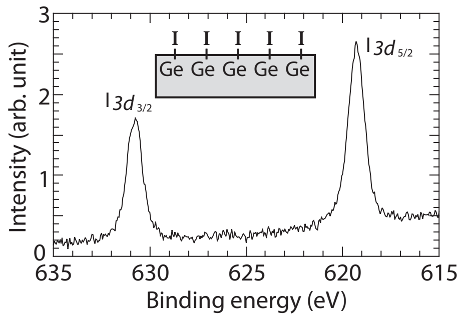

Fig.3 I *3d* XPS spectra of the Ge substrate treated by the I_2 solution (0.005 mol/L).

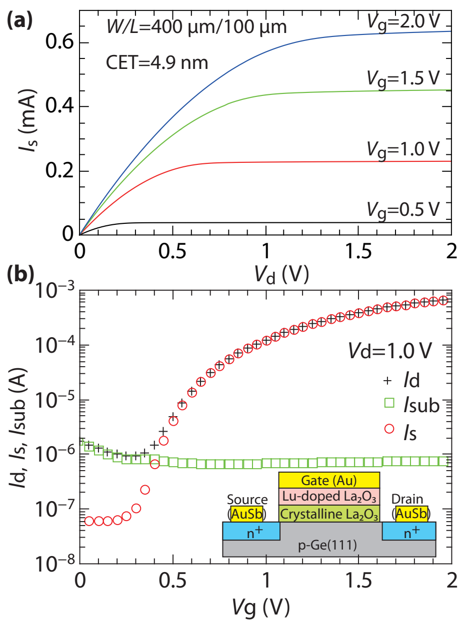

Fig.4 (a) I_s-V_d and (b) I_d, I_{sub}, I_s-V_g characteristics of the Ge-MISFET treated by the I_2 solution (0.005 mol/L).

Figures 4(a) and (b) show the I_s-V_d and I_d, I_{sub}, I_s-V_g characteristics of the Ge-MISFET treated by the I_2 solution of low concentration. Reasonable electrical properties are obtained, and the value of sub-threshold swing (SS) of 128 mV/dec is smaller than that of the conventional sulfur treatment of 156 mV/dec. This indicates that the I_2 treatment is effective for the improvement of interface properties.

4. Summary

Low D_{it} of ~5×10^{11} $cm^{-2}eV^{-1}$ was obtained when Ge substrates were dipped into the I_2 solution of 0.005 mol/L before crystalline La_2O_3 growth in comparison with the conventional sulfur treatment. The AFM and XPS measurements revealed that their improvements were caused by the reduction of surface roughness and iodine termination on the Ge surfaces. Moreover, enough stability was shown and improved Ge-MISFET properties were obtained by using this method.

Acknowledgments

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