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Quantitative Evaluation of Interface Trap Density in Ge-MIS Interfaces

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1. Introduction

Ge-channel MOSFETs have recently attracted much attention because of the high carrier mobility. However, the Ge-MOS or MIS interface properties have not been investigated in great detail compared to a Si-MOS interface because a evaluation method for a Ge-MIS interface have not been establish yet. As a reason, high intrinsic carrier density (2.4×10^{13} cm^{-3}) of Ge at room temperature (RT) due to a narrow bandgap (0.66eV)[1] is known to significantly affect C-V characteristics [2] and, thus, to make it difficult to apply conventional methods of evaluating interface trap density, based on C-V analyses, to Ge-MIS capacitors because of anomalous C-V curves[3,4]. Since the realization of good MIS interface properties is one of the most important issues on Ge MOSFETs, accurate evaluation techniques of interface trap density suitable for Ge-MIS interfaces is strongly needed. For this purpose, we systematically examine the C-V and G-V methods at various temperatures for Al/SiO_2/Ge-MIS structures with different interface structures. As a result, it is demonstrated that the conductance method including the effects of the surface potential fluctuation and the HF-CV (Terman) method at low temperatures can provide accurate interface trap density for Ge-MIS capacitors with various interfaces.

2. Experimental

First, Ge(001) wafers were cleaned with alkaline solution and dilute HF. Ge wafers were exposed to N_2, H_2, O_2 or NH_3 in 720 Torr at 420°C for 30min. Subsequently, a 10-nm-thick SiO_2 layer was deposited by low-pressure chemical vapor deposition, and a capacitor with an Al gate electrode was fabricated. Each sample is denoted by the ambient gas employed. For example, a sample annealed in N_2 ambient is called the sample N_2. TEM and XPS were used to characterize interface structure, and electrical characteristics were measured at various temperatures.

3. Results and Discussion

Cross-sectional TEM images of the samples N_2 and O_2 are shown in Fig. 1(a) and (b), respectively. In Fig. 1(a), an interface layer between SiO_2 and Ge surface can not be observed. Also similar results were observed in the samples H_2 and NH_3. On the other hand, an interface layer and significant surface roughness can be clearly observed in Fig. 1(b). By XPS measurements, the interface layer consists of GeO_2, and, ultrathin GeO_x, and GeO_xN_y layers which are not visible by TEM, are also observed at the interfaces in the samples N_2 or H_2 and NH_3, respectively.

Figures 2(a) and (b) show C-V curves of the sample N_2 measured at (a) 25°C and (b) -60°C, respectively. It is observed in Fig. 2(a) that the frequency dispersion is large in the bias voltage range from -1 to -3V, while, the frequency dispersion is not observed at -60°C. Very similar results were obtained in every sample. In Fig. 2(a), the frequency dispersion in inversion region is caused by response of minority carriers. By decreasing the measurement temperature, the response is suppressed because intrinsic carrier density decreases at low temperature. Figure 3 shows the dependence of the capacitance at midgap voltage on frequency for the sample N_2 at various temperatures. It is found that the frequency dispersion is hardly observed at less than -25°C and more than 10kHz. This suggests that interface traps can not respond below -25°C and above 10kHz at midgap Those makes it very difficult to apply the Terman method at RT, because C-V curves under high frequency extreme cannot be obtained even at 1 MHz.

In order to determine an appropriate measurement method of interface trap density in Ge-MIS capacitors, the results evaluated by two typical measurement techniques, the Terman and the conductance methods, are compared at two measurement temperatures. The energy distributions of interface trap densities for the each sample are shown in Fig. 4(a) to (d). Here, C-V curves at 1MHz and equivalent parallel conductance (G_p/ω)-frequency (G-f) curves at 25°C and -60°C are used for the Terman and the conductance methods including the effects of surface potential fluctuation, respectively. It is confirmed in the sample N_2 that the interface trap densities evaluated from the Terman method at 25°C is higher than that of the other cases in especially band-edge. This means that the Terman method based on the C-V data at 25°C can not accurately measure the interface trap density because interface traps respond ac signals even 1MHz as seen in Fig.3. On the other hand, the distributions measured by the Terman method at -60°C are in good agreement with those measured by the conductance method. Similar tendency is confirmed in the samples H_2 and NH_3. However, in the sample O_2, the distribution by the Terman method measured at -60°C does not correspond to other distributions. Although causes of the disagreement have not been clear yet, it is considered that stretch out of C-V curves is induced by surface potential fluctuation due to surface roughening as seen in Fig.1(b) and/or impurity redistribution during oxidation [5].

Figure 5 shows G_p/ω measured at 25°C and -60°C as a function of frequency near -0.1eV from the midgap [the arrow in Fig. 6(a)] of the sample N_2. The G-f curve measured at -60°C is broader than that measured at 25°C and the maximum value is lower. Figure 6(a) shows the energy distributions of the interface trap densities for the sample N_2 measured at 25°C and -60°C without including effects of the surface potential fluctuation. The distributions and the values of the densities are apparently different with both temperatures, because the increase in the surface potential fluctuation and resulting broader G-f curve is known to lead to the decrease in the peak value of G_p/ω [6]. Figure 6(b) shows those including the effect of the surface potential fluctuation. It is found that the difference in the energy distributions of the interface trap density almost disappears by taking the effect of the decrease in the peak in G_p/ω due to the surface potential fluctuation into account.

As a result, the coincidence among the different evaluation methods for Ge-MIS capacitors with various interfaces guarantees the validity and accuracy of the present results and evaluation methods.

4. Conclusions

Accurate evaluation methods of interface properties for Ge-MIS structures have been proposed in this study. It is concluded that the conductance method including the correction due to G-f curve broadening and the Terman method using C-V data at sufficiently low temperatures are accurate techniques for evaluating the interface trap density of Ge- MIS interfaces.

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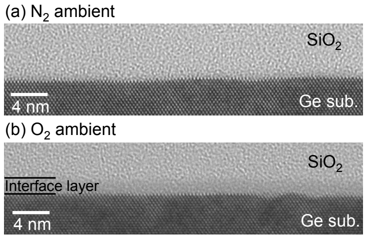

Fig. 1: Cross-sectional TEM images of the samples (a) N_2, (b) O_2, respectively.

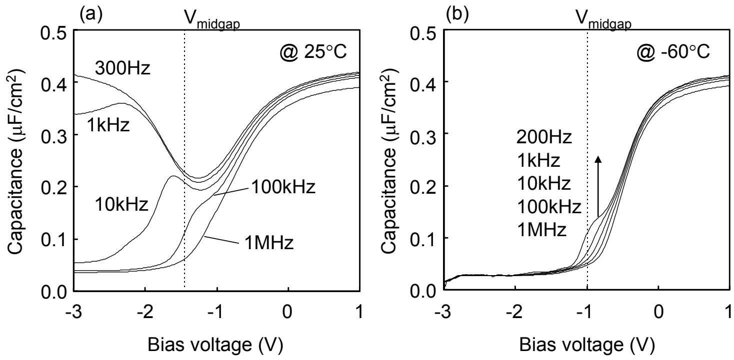

Fig. 2: C-V curves of the sample N_2 measured at various frequencies at (a) 25°C and (b) -60°C

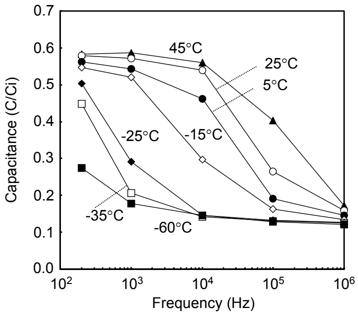

Fig. 3: Dependence of capacitance at midgap voltage on frequency for the sample N_2 at various measurement temperatures.

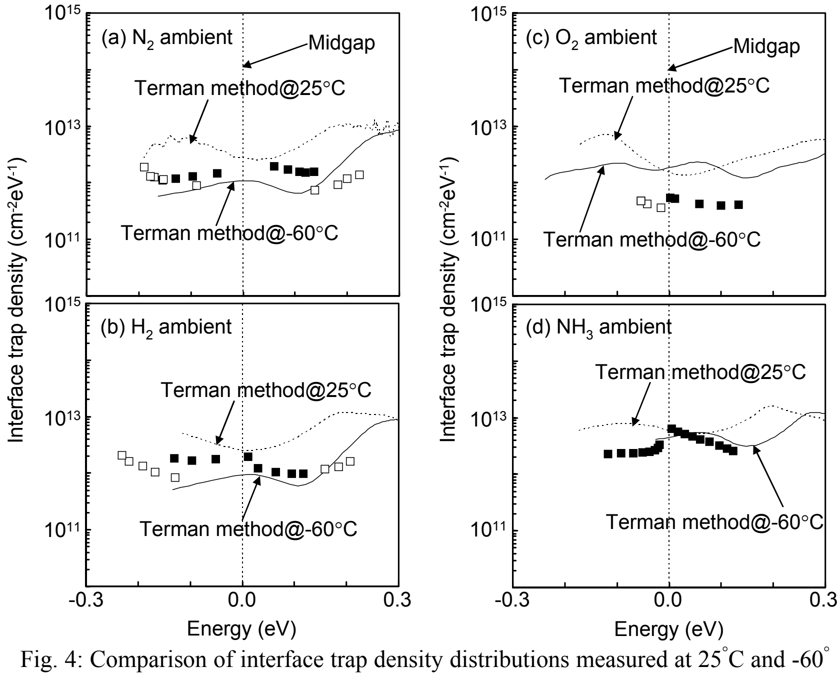

Fig. 4: Comparison of interface trap density distributions measured at 25°C and -60°C of the samples (a) N_2, (b) H_2, (c) O_2 and (d) NH_3 by using Terman and the conductance methods, where (■) and (□) indicate results of the conductance method at 25°C and -60°C, respectively.

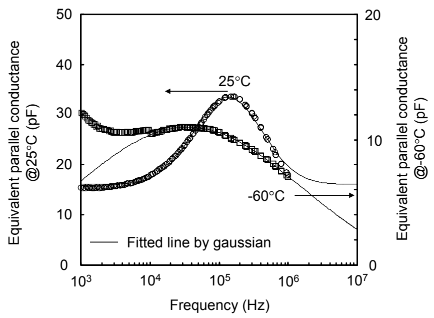

Fig. 5: Equivalent parallel conductance (G_p/ω) measured at 25°C and -60°C as a function of frequency.

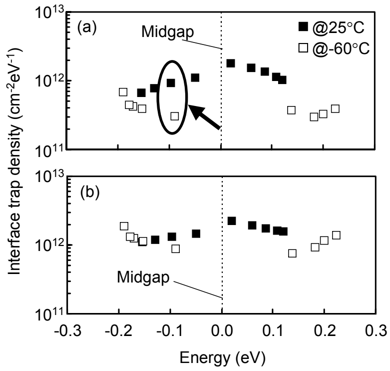

Fig. 6: Interface trap density distributions measured at 25°C and -60°C (a) without including the effect of the surface potential fluctuation and (b) including that.