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Leakage Current Control of Fluoride Ultra-thin Films Grown on Ge Substrates

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1. Introduction

Resonant tunneling diodes (RTDs) composed of ultra-thin fluoride heterostructures on Si such as $CaF_2/CdF_2/CaF_2/Si$, in which CaF_2 layers are double barrier layers and CdF_2 layer is quantum well layer, are promising candidates for quantum devices co-integrated with Si integrated circuit [1, 2]. However, large chemical reactivity between CdF_2 and Si is a significant problem, which leads instable electrical properties of the devices due to very low growth temperature around room temperature (R.T.) to avoid the chemical reaction.

As a solution of the problem, use of substrates other than Si substrates, which are chemically inactive for CdF_2, is expected. Ge is a good candidate from this view point. Therefore, use of higher growth temperature to improve quality of the grown fluoride layers is expected on Ge substrates. Furthermore, since Ge can be used as not only bulk substrate but also a buffer layer on Si substrate, this approach will be useful for high quality RTDs on Si substrates in future.

Recently, we developed epitaxial growth technique for thin fluoride barrier layers on Ge substrates, in which $Ca_{0.42}Sr_{0.58}F_2$ alloy is employed instead of pure CaF_2 and it is grown by the two-step growth method to obtain smooth surfaces [3]. The alloy composition is corresponding to lattice match condition for Ge. However, we also found a problem of large leakage currents for the $Ca_{0.42}Sr_{0.58}F_2$ layers on Ge substrates. In this work, we revealed a possible origin of the leakage currents of fluoride layers peculiar to growth on Ge. And we propose a new technique to reduce the leakage current of fluoride barrier layers grown on Ge substrates.

2. Experimental Procedures

Single layers of 5-nm-thick $Ca_xSr_{1-x}F_2$ were grown on heavily doped N-type Ge(111) and Si(111) substrates by using a solid source molecular beam epitaxy system. The growth methods are deposition at R.T. or the two-step growth method [3], that is, deposition at R.T. followed by *in situ* annealing at proper temperature.

Double layer structures composed of an initial 0.67-nm-thick SrF_2 layer and a 4.33-nm-thick $Ca_xSr_{1-x}F_2$ over layer were also grown by the R.T. deposition method and the two-step method on the Ge and Si substrates.

For these growths, alloy composition, x, of $Ca_xSr_{1-x}F_2$ was varied from 0 (pure SrF_2) to 1.0 (pure CaF_2), and x=0.42 is lattice match condition for Ge while x=1.0 is that for Si approximately.

Grown surfaces were characterized by atomic force microscopy (AFM), and leakage current properties of the fluoride layers were evaluated by *I-V* characteristics measured on MIS diodes in which 200 μm ϕ Al electrodes over coated by Au were deposited on the grown surfaces.

3. Results and Discussion

Figure 1 shows *I-V* characteristics of the $Ca_{0.42}Sr_{0.58}F_2$ layers grown on Si and Ge substrates by the two-step growth method with annealing at 300°C, which is an optimized condition in the previous work [3]. The *I-V* characteristics were represented by geometric means of characteristics of multiple diodes having the same structure and growth condition. The leakage current on the Ge substrates was obviously larger than that on the Si substrates. Figure 2 shows the surface morphologies of these fluoride layers. The surface of grown layer on Si substrate was very smooth, while that on Ge substrate was rough. Therefore, there is a possibility that the large leakage current on Ge substrates is enhanced by the surface roughness due to existence of localized thin regions. In

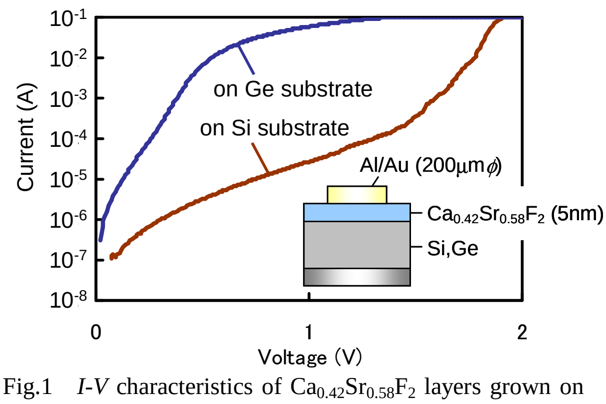

Fig.1 *I-V* characteristics of $Ca_{0.42}Sr_{0.58}F_2$ layers grown on Ge and Si by the two-step growth method with annealing at 300°C.

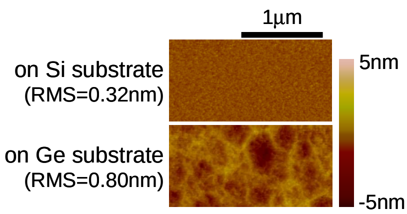

Fig.2 AFM images of surface morphologies of $Ca_{0.42}Sr_{0.58}F_2$ layers grown on Ge and Si by the two-step growth method with annealing at 300°C.

order to compare leakage currents depending on the substrate eliminating the effect of surface roughness, that is, nonuniformity of layer thickness, growth at very low temperature was examined, although epitaxial growth was not achieved. The $Ca_xSr_{1-x}F_2$ layers (x=0, 0.2, 0.42 and 1) were grown at R.T. on Si and Ge substrate. Figure 3 shows the dependence of the leakage currents represented by geometric means of current at bias of 1V on alloy composition of $Ca_xSr_{1-x}F_2$. The leakage currents on Si and Ge substrates were low and same level for x=0 (SrF_2). However, at x larger than 0.2, the leakage currents on Ge substrates increased enormously while those on Si substrates were small for all composition. The fluoride layers on both substrates exhibited smooth surface as shown in Fig.4. Therefore, it is considered that the still large difference in the leakage currents for x>0.2 reflects the properties of the bulk fluorides. And the result strongly indicates that existence of CaF_2 fraction degrades electrical insulation only on the Ge substrates.

For the purpose of confirmation of the idea and reduction of the leakage current on Ge substrates, the double layer structure in which a thin SrF_2 buffer layer was introduced at the interface between $Ca_xSr_{1-x}F_2$ layer and Ge substrate. Figure 5 shows the dependence of the leakage currents on alloy composition of $Ca_xSr_{1-x}F_2$ layer for the double layer structure grown at R.T. The leakage currents on the Ge substrates were reduced drastically down to the same level of those on Si substrates for all compositions.

Furthermore, the double layer structure was found to be very effective in the case of the two-step growth with annealing at 250°C, as shown in Fig.6, in which $Ca_{0.42}Sr_{0.58}F_2$ layers grown on Ge substrate exhibited

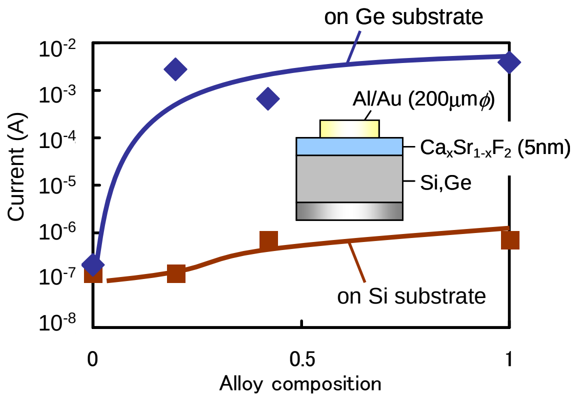

Fig.3 Dependence of leakage currents of the single layer structure grown at R.T. at 1V bias on alloy composition: x of $Ca_xSr_{1-x}F_2$.

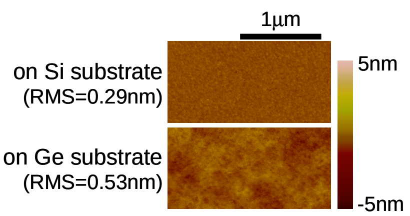

Fig.4 AFM images of surface morphologies of $Ca_{0.42}Sr_{0.58}F_2$ layers grown at R.T. on Ge and Si

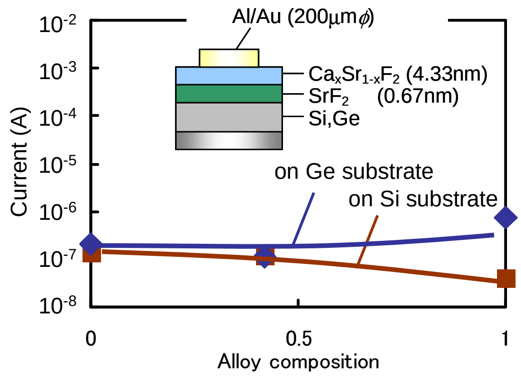

Fig.5 Dependence of leakage currents of the double layer structure with SrF_2 buffer layer grown at R.T. at 1V bias on alloy composition: x of $Ca_xSr_{1-x}F_2$.

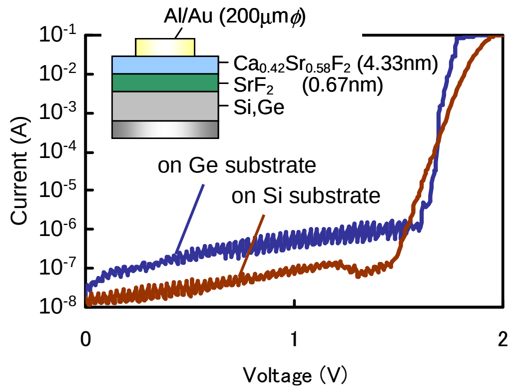

Fig.6 *I-V* characteristics of the double layer structures. The fluoride layers were grown by the two-step growth method with annealing at 250°C.

leakage current as low as that on Si substrate. This result indicates that this technique is useful for epitaxial growth of fluoride layers containing CaF_2 fraction on Ge substrates and high temperature growth of fluoride heterostructure on Ge substrate is expected with this technique.

4. Conclusion

The leakage currents of $Ca_xSr_{1-x}F_2$ layers on Si substrates were small for all composition while those on Ge substrates were enormously large for x larger than 0.2. It predicts that existence of CaF_2 fraction degrades electrical insulation only on the Ge substrates. Introduction of the very thin SrF_2 buffer layer was effective to reduce the leakage current. This technique will be useful to fabricate fluoride quantum well devices on Ge substrates.

Acknowledgement

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