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MBE Growth and Electrophysical Characterization of Pseudomorphic CaF_2/Si(111) Structures

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Pseudomorphic CaF_2 layers were grown on n-Si(111) substrates by MBE with the characterization of crystalline quality by electron diffraction. Current-voltage characteristics of Au/CaF_2/Si structures were studied in a dark and under illumination. The characteristics of the structures with the fluorite layer thinner than 6 nm showed effect of a phototransistor with a tunnel MIS emitter and induced base. The pseudomorphic fluorite layers sustain electric field up to 5 MV/cm and tunnel current 0.1 A/cm^2 under illumination.

1. INTRODUCTION

Single crystal fluoride films grown by molecular beam epitaxy (MBE) on semiconductors attract the attention of researchers due to various promising applications in microelectronics and fundamental interest to properties of crystalline insulator/semiconductor interface. Previous electrophysical studies were mainly devoted to MIS structures with relatively thick (more than 50 nm) fluoride layers [1] which were used as gate insulators in MISFETs on Si [2] and GaAs [3]. Because of high defect concentration induced by lattice mismatch and thermal stress relaxation electrophysical properties of these structures were not good enough for device applications. Another possible application is to use these layers as current conducting (e.g. tunnel) MIS structures. Crystallinity of fluoride films allows to expect more favorable conditions for charge transport through CaF_2 than through amorphous insulators as SiO_2. In the present paper we studied the MBE growth of thin (less than 10 nm) fluorite films on silicon and current-voltage (I-V) characteristics of the MIS structures in a dark and under illumination.

2. EXPERIMENTAL

The CaF_2/Si layers were grown in a research MBE system equipped with reflection high energy electron diffraction (RHEED) apparatus. The phosphorus doped 5 Ohm.cm silicon substrates were etched and passivated in acid peroxide solution. The protective oxide was removed by heating the substrates at 1250^{0}C, then RHEED patterns from Si(111) surface exhibited 7x7 reconstruction at temperatures lower than 830^{0}C. Pure CaF_2 was evaporated from carbon glass crucibles, fluorite deposition rate was 2 to 3 nm/min. For electrophysical studies each film was capped at room temperature with an array of Au spots 100 nm thick and 10^{-3}cm^2 in size. The design of the structures is shown on the inset in the fig.2.

3. RESULTS AND DISCUSSION

As it was first shown in [4] CaF_2 films can be grown pseudomorphic (coherent) to silicon substrate. There were grown pseudomorphic layers as thick as 30 nm when the growth began at high temperature 750^{0}C and finished at low temperature 120^{0}C.

Similar growth process was carried out in the present study. The first two fluorite monolayers were deposited at 770^{0}C to form well ordered CaF_2/Si(111) interface, then fluorite molecular cell was closed, the structure was cooled to 300^{0}C, and the growth was continued. Streaks on RHEED pattern indicated atomically smooth surface of the single crystal film. RHEED intensity oscillations showed layer by layer fluorite growth (fig.1). Each period of the oscillations corresponds to the growth of one triple F-Ca-F monolayer (0.315 nm). This allows to measure the film thickness with the monolayer precision [5].

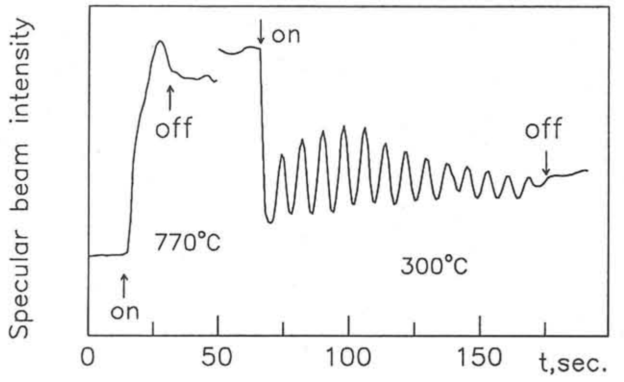

Fig.1. RHEED intensity oscillations during the growth of pseudomorphic $CaF_2/Si(111)$ structure. Electron energy 15 keV, beam azimuth [112].

The fluorite films grown at such conditions were demonstrated to be pseudomorphic with silicon substrate by rare earth ion photoluminescence measurements [5]. Absence of misfit dislocations and reduced defect concentrations related to them are appropriate to such growth mode.

The current-voltage measurements of Au/CaF_2/n-Si structures give typical results plotted in fig.2. The current through a pseudomorphic layer at forward (Au plus) bias (curve a) has normal exponential dependence. At a reverse (Si plus) bias there is only leakage current (curve b) because of small voltage drop on the insulator, fig.3a (the drop is a product of electric field in depletion layer by small insulator thickness). The measurements revealed that the layers from 3 to 6 nm thick can sustain an electric field up to $5x10^6$ V/cm.

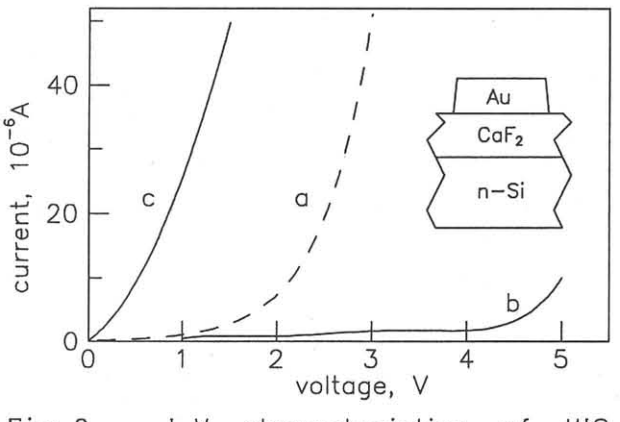

Fig.2. I-V characteristics of MIS structures Au/CaF_2 5 nm/n-Si a) coherent, forward bias, b) coherent, reverse bias , c) relaxed, any bias.

There is Ohmic dependence of current on applied voltage in thicker fluorite layers or in those grown at higher temperatures (5 nm at 770°C for fig.2c) when a breakdown of pseudomorphic growth mode occurs. Misfit dislocations with their ends penetrating a relaxed layer can be the ways for current conduction. Leakage current through MIS structures with such layers is at least an order of magnitude higher than that through the coherent structures.

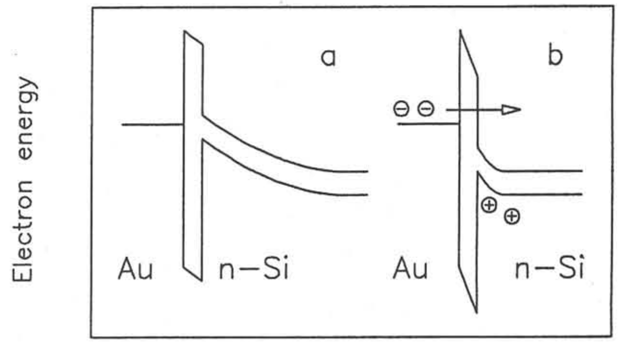

Fig.3. Energy band diagram of reverse biased Au/CaF_2/n-Si heterostructure a) in a dark, b) under illumination.

Under illumination ($h\nu > E_g^{Si}$) of the reverse biased structure the insulator voltage drop becomes considerable due to high hole density at CaF_2/Si interface with inverted conductivity, fig.3b. Conduction band minimum begins to lower down below the Fermi level of the metal, increasing the injection of electrons through the tunnel-thin insulator and induced base into the collector. The base width is about 1 to 1.5 nm [6]; it is less than mean free path of electrons (~10 nm), therefore, they pass through the base ballistically.

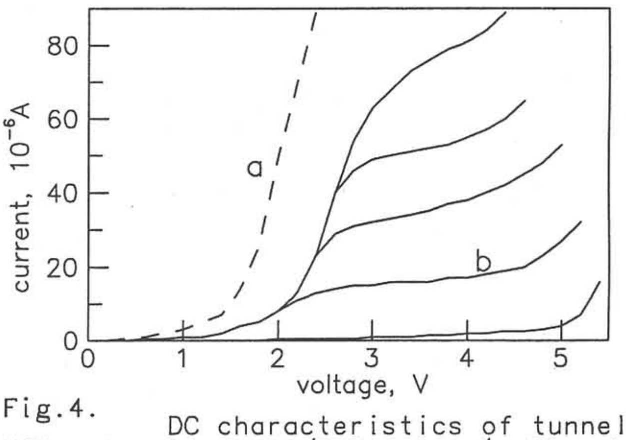

Fig.4. DC characteristics of tunnel MIS structure Au/CaF_2 4 nm/n-Si at different intensity of illumination; forward bias (dashed), reverse (solid).

Fig.4 presents typical I-V characteristics of Au/CaF_2/n-Si(111) structuct at different intensities of illumination. The characteristics are similar to those observed in [7] in active mode of Al/SiO_2/n-Si tunnel ballistic transistors. Thus our structures may operate as a phototransistor with tunnel MIS emitter, inversion layer as induced base and the substrate as a collector. Note, that the voltage applied to the structure in saturation mode is high: several volts, depending on the current density and CaF_2 thickness. This voltage is approximately equal to the sum of insulator voltage drop (several volts) and inversion hole layer voltage drop (~0.5 V [6] or less).

Ballistic phototransistor characteristics were observed in tunnel MIS structure with insulator thickness up to 6 nm. The reproducibility of the device characteristics reduced considerably with CaF_2 thickness increase even within one array on the same heterostructure. Leakage current through the investigated transistors with thin insulator layers was rather small (Fig.6) but in the case of a thicker (>6 nm) insulator layer it was much higher. This may be related to the deterioration of the CaF_2 layer crystalline quality due to initial stages of misfit stress relaxation under an influence of thick gold layer.

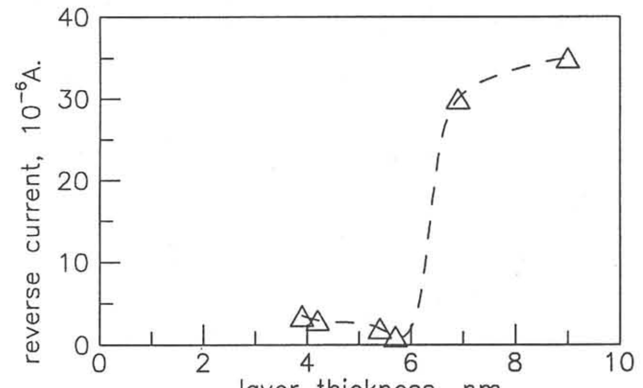

Fig.5. Leakage current through the MIS structures of different thickness; device area $10^{-3}cm^2$, reverse bias 3 V.

As it was found in Al/SiO_2/n-Si structure [7], if insulator voltage is high enough, the electrons tunnelling from the metal into the semiconductor conduction band pass through the induced base ballistically and can possess an energy which is quite enough for multicascade Auger ionization. It results in increase of current gain [6,7], negative differential resistance [8], switching unto "ON" state [8,9], and multistability of the transistor.

In Au/CaF_2/n-Si structure we have not observed these effects, but some features of our I-V characteristics can be attributed to Auger ionization. It is a steep current rise which can be observed in each I-V curve under illumination in active mode of the transistor. When the light intensivity becomes higher, this sharp rise shifts toward the smaller collector voltage. This shift is because insulator voltage drop becomes higher therefore injected hot electrons need smaller additional energy obtained in space charge region in order to be capable of Auger ionization. (Auger ionization probability depends both on initial electron energy and on additional energy obtained in electric field).

4. CONCLUSION

CaF_2 pseudomorphic layers on Si(111) grown by MBE in two-stage process were demonstrated to have attractive parameters for device application. Current-voltage measurements of Al/CaF_2/n-Si heterostructures revealed the effect of a phototransistor. The transistor is formed by tunnel MIS emitter, ballistically thin induced base and the substrate as a collector. Larger CaF_2 band gap in respect to SiO_2 allows to expect higher emitter efficiency and better parameters of the transistor.

5. REFERENCES

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