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ELECTRONIC AND MECHANICAL PROPERTIES OF Ge FILMS GROWN ON GLASS SUBSTRATES

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ABSTRACT

As germanium is closed lattice matched to GaAs, it a suitable substrate for epitaxial growth. In the quest for inexpensive substrates, thin-film Ge grown on glass is an attractive candidate if suitable grain growth can be achieved. Here we will describe Ge films that are deposited by an e-beam evaporator on glass and are approximately 2000 Å thick. The films were annealed at 500° C and 600° C to improve the quality of the material. The growth was done in three steps with 1000 Å of Ge, 70 Å of Sb, and followed by another 1000 Å angstroms of Ge. Sb is an n-type dopant in Ge and is included to enhance grain growth. The best films contained the Sb layer and hole concentrations between $1.4x10^{15}$ to $1.6x10^{17}$ cm^{-3}. The largest hole mobility measured was 30.6 cm^2/Vs in the $1.4x10^{15}$ p-type sample. The electron lifetime was measured by ultra-high frequency photoconductive decay and the best lifetimes were in the 30- to 40-ns range. Scanning-electron microscope and transmission-electron microscope studies indicated a polycrystalline grain structure with grain size comparable to the film thickness.

INTRODUCTION

A key component in the commercialization of the III-V epitaxial growth technologies is the development of low-cost substrates. If such substrates can be invented and substituted for the high-cost wafer, the cost of these solar cell technologies would be greatly reduced. This project is a component of an effort to develop a low cost substrate for high-efficiency III-V semiconductor solar cells [1]. The goal here is to explore the properties of thin Ge films grown on glass substrates as a template for the growth of epitaxial GaAs.

Sample Preparation

The Ge films were grown using a 99.999%-pure Ge source in an e-beam evaporator at typical pressures of $2x10^{-6}$ Torr. We first considered the effect of annealing the Ge films after evaporation because the as-evaporated Ge film were nearly amorphous as evidenced by the absence of any x-ray reflections and the extremely low mobility of carriers. All as-evaporated films as well as the annealed Ge films tend to be p-type. Table 1 summarizes the effect of thermal annealing on the properties of Ge films on glass substrates. These films are approximately 2040-Å thick and are p-type.

From the data in Table 1, we observe that the thermal annealing clearly improves the quality of the Ge films, indicated by the fairly large hole mobility along with the strong increase in carrier concentration. This leads to an improvement of electrical conductivity by over four orders of magnitude. The improvement in electrical transport properties is accompanied by the clearly observed polycrystallinity of the Ge films. However, we observe no preferred orientation of the crystallized films.

We also investigated the use of a Ge/Sb/Ge sandwich structure that was deposited by evaporation. Sb is an n-type dopant in Ge, and like Ge, and unlike other n-type dopants such as P and As, it can be easily evaporated. Also, the n-type doping may be beneficial to enhanced grain growth. The structure was made by first depositing 1000 Å of Ge followed by 70 Å of Sb, and followed by another 1000 Å of Ge. The structure was then annealed to intermix the components.

The annealing times and temperatures, as well as the resistivity and Hall mobility, are shown in Table 2.

Examination of Grain Structure By Electron Microscopy

Two of the annealed “sandwich” films were analyzed by scanning-electron microscopy (SEM) and transmission electron microscopy (TEM). Film GT 8-3 was highly photoconductive, whereas film GT 8-14 was not photoconductive. The photoconductive properties will be discussed in the next section. SEM examination showed that these films are specular with very low surface roughness. TEM specimens were prepared by thinning the glass substrates, gluing pieces of the samples to Si, dimpling, and subsequent ion milling. The TEM analysis showed polycrystalline texture in both films (GT 8-3 and GT 8-14), with the Ge grains predominately displaying the diamond structure. The characteristic selected-area diffraction ring pattern acquired in cross section from GT 8-14 is shown in Fig. 1. We do not detect significant diffuse scattering in the diffraction that would result from

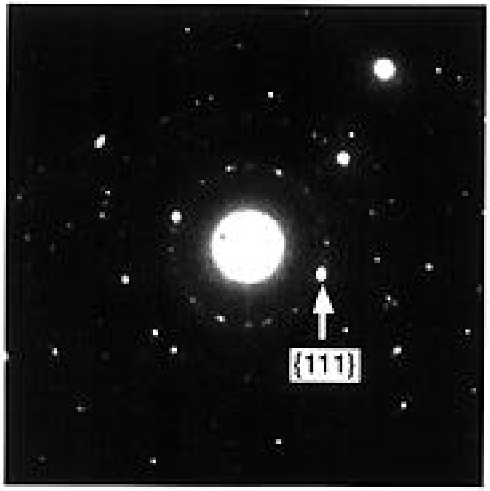

Fig. 1. Selected-area diffraction pattern from TEM cross section of polycrystalline Ge film on glass.

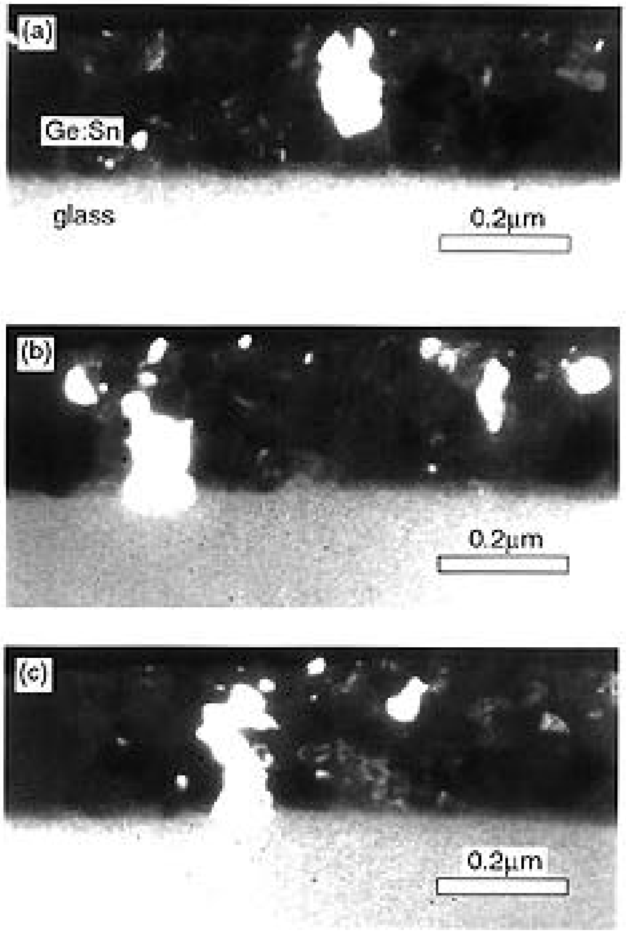

Fig. 2. Conical {111} dark-field series from a single region of polycrystalline Ge film showing submicron grain sizes.

amorphous regions, indicating nearly complete recrystallization of the amorphous films.

The TEM results do not reveal a preferred grain orientation with respect to the substrate. Fig. 2 shows dark-field images acquired from GT 8-3 using the {111} reflection in conical mode. The grain profiles appear irregular and random. The maximum grain sizes are roughly equal to the film thicknesses, which are about 2200 Å for both films, while many very small grains (<200 Å) were present throughout the films. Bright-field images reveal that the film is structurally dense, showing no apparent pores or cracks. The film surface is relatively flat, with a variation of less than about 100 Å. Images and diffraction patterns from the two samples show that the average grain size is somewhat larger in GT 8-3 than GT 8-14. The distribution of Sn within the films was not clearly revealed by x-ray microanalysis.

Measurement Of Minority-Carrier Lifetime

The minority-carrier lifetime of these films was measured by the RFPCD technique that has been described [2,3]. The pulsed excitation source used here is a YAG laser operating at the fundamental wavelength of 1064 nm. The signal that is produced and detected by the measurement system is given by:

$$\Delta\sigma = q(\mu_n + \mu_p)\rho(t). \tag{1}$$

Here μ_n (μ_p) are the electron (hole) mobilities and $\rho(t)$ is the excess carrier concentration. The signal amplitude is proportional to excess carrier density and the electron and hole mobilities.

When the recombination mechanism can be written in terms of a single lifetime τ, then:

$$\Delta\sigma = q(\mu_n + \mu_p)\rho_0 \exp(-t/\tau). \tag{2}$$

We used the RFPCD technique to measure the room-temperature recombination lifetime of excess carriers in the thin films described above. The laser power per pulse was varied from less than 0.1 mJ to approximately 1 mJ using a pair of rotating polarizers as variable attenuators. The laser-beam diameter is about 5 mm.

Our RFPCD measurements indicated no photoconductive response from any of the films that did not contain Sb. Also, no response was found for any of the unannealed films. However, fairly strong photoconductive response was found for films labeled GT 8-3 and GT 8-5.

For films with no appreciable grain growth, the minority-carrier lifetime will most likely be very small and will be dominated by recombination at grain boundaries. Several of the Ge/Sb/Ge films (GT-8, for example) had electron lifetimes that were in the 30-to-40 ns range as seen Fig. 3. These data imply that the grain growth is occurring during the processing. The amplitude of the RFPCD signal also indicated that the minority-electron mobility was appreciable. These data are shown in Fig. 3. The signal amplitude indicates that the minority-carrier (electron) mobility is also as

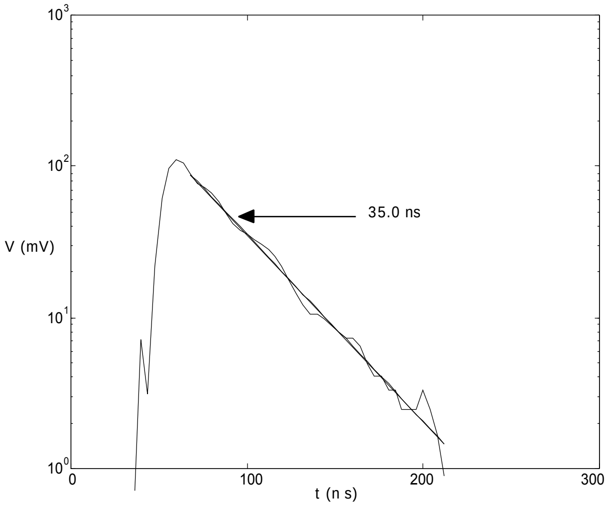

Fig. 3. The RFPCD response of a Ge/Sb/Ge sandwich film using 355 nm pulsed laser excitation.

large or larger than the hole mobility. These films then have electronic properties that make them viable device materials and serviceable substrates for epitaxial growth.

CONCLUSION

Thin film Ge, with promising structural and electronic properties, has been grown on glass substrates by e-beam deposition. Annealing produces recrystallization with grain sizes up to 200 Å in diameter. Hole mobilities as large as 44 cm^2/Vs were measured. Minority-carrier lifetimes in the range of 30 to 40 ns were also measured in the best films along with appreciable photoconductive response. In total, these results indicate that these films are promising both as substrates for epitaxial growth and as independent electronic materials.

ACKNOWLEDGMENTS

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Table 1. Effect of thermal annealing on the properties of Ge films on glass. All Ge films are approximately 2040-Å thick and p-type.

#	T(°C)	(min)	μ_p	p(cm-3)	ρ	X-ray	111/220
GT 7-2	550	5	24.4	4.3E18	6.0E-2	Poly	2.06
GT 7-5	550	15	30.8	3.8E18	5.3E-2	Poly	1.96
GT 7-6	550	30	30.2	4.3E18	4.8E-2	Poly	2.03
GT 7-4	600	5	38.0	3.8E18	4.4E-2	Poly	1.78

Table 2. Effect of thermal annealing on the properties of Ge/Sb/Ge sandwich structures on glass.

#	T(°C)	(min)	μ_p	p(cm-3)	ρ	X-ray	111/220
GT 8-1	530	5	2.8	6.8E17	3.27	Poly	2.57
GT 8-2	550	5	1.15	3.8E16	142	Poly	2.94
GT 8-3	600	5	9.5	3.3E15	198	Poly	4.2