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LOW TEMPERATURE EPITAXIAL GROWTH OF $CoGe_2$(001)/GaAs(100) FILMS USING THE PARTIALLY IONIZED BEAM DEPOSITION TECHNIQUE

K. E. MELLO
S. R. SOSS
S. P. MURARKA
T.-M. LU
S. L. LEE

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US ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
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K.E. Mello (RPI, Troy, NY), S.R. Soss (RPI),
S.P. Murarka (RPI), T.-M. Lu (RPI), and S.L. Lee

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13. ABSTRACT *(Maximum 200 words)*

The partially ionized beam (PIB) deposition technique was used to deposit $CoGe_2$(001) thin films heteroepitaxially on GaAs(100) substrates for the first time. The epitaxial arrangement was $CeGe_2$(001)/GaAs(100). It was found that the best epitaxy was obtained with an ion energy around 1100 eV and with a substrate temperature of 280°C. The wafers were treated only by immersion in $HF:H_20$ 1:10 immediately prior to deposition. Contacts grown at the optimal epitaxial formation conditions displayed ohmic behavior, while contacts grown at higher or lower substrate temperatures had rectifying behavior. Epitaxial formation of $CeGe_2$, a high-melting point, low resistivity cobalt germanide phase, offers the possibility of forming a stable contact to *n*-GaAs.

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INTRODUCTION

Contacts to *n*-GaAs leading to ohmic or rectifying behavior are technologically important for electronic and optoelectronic devices and circuits. Ideally, the ohmic contact should supply the required current with a voltage drop that is sufficiently small compared to the drop across the active region of the device, so as not to significantly disturb device operation (ref 1). During GaAs device fabrication, annealing temperatures routinely reach about 400°C, and can be as high as 600° to 800°C for solar cell and self-aligning device processing (ref 2). The problem is thus one of producing a thermally stable and reliable contact.

For *n*-GaAs no elemental metal offers a low Schottky barrier height. The most commonly used ohmic contact to *n*-GaAs includes a system based on the Au-Ge eutectic. When an Au-Ge film on GaAs is heated to the eutectic temperature (356°C), an ohmic contact is formed. Au-Ge, however, does not easily wet GaAs. To promote wetting, small amounts of Ni (from 2 to 11 wt%) are added during deposition. Many other schemes of ohmic contact formation have been conceived (refs 2-12), but most require metallurgical interaction with the GaAs (alloying) induced by a high temperature (often >400°C) thermal anneal.

We report herein on the deposition of an epitaxial layer of a cobalt germanide, $CoGe_2$, on GaAs to form the heteroepitaxial system $CoGe_2$(001)/GaAs(100). This phase offers a low-lattice mismatch (-0.2 percent) with GaAs, and has been shown, in bulk form, to be the minimum resistivity phase of all the cobalt germanides with a polycrystalline resistivity of 35 $\mu\Omega \cdot cm$ (ref 13), a value comparable to that of $CoSi_2$. In addition, $CoGe_2$ has a high melting temperature (806°C), hence single-crystal contacts of this phase promise excellent high temperature thermal stability. Sequential sputtering of Co and Ge followed by an anneal to produce Ge-rich Co-Ge contacts has been investigated by other researchers, however, the anneal step was shown to induce chemical interaction with the GaAs and in most cases, produced rectifying behavior for the contacts (refs 14, 15).

EXPERIMENTAL PROCEDURE

The epitaxial films were deposited on semi-insulating, epi-ready GaAs(100) wafers. For electrical measurements, 4.42×10^{-3} cm^2 dots were deposited through a shadow mask onto Si-doped GaAs(100) wafers with a carrier concentration of $(1\text{-}4) \times 10^{18}$ cm^{-3}. Wafer cleaning was a simple 30-second $HF:H_2O$ 1:10 dip immediately prior to deposition. The partially ionized beam (PIB) deposition technique has previously been described (ref 16). Briefly, Ge is placed within a graphite crucible that is surrounded by a Ta filament. Thermionically-emitted electrons bombard the crucible because of the application of a high positive voltage. Some of the electrons from the filament also sail over the mouth of the crucible impact ionizing <2 percent of the exiting vapor stream. These ions are then accelerated by a potential applied to the substrate. The Ge^+ ions arrive with an energy given by the potential drop between the crucible and substrate and are deposited along with the neutral Ge species and the Co, which is conventionally evaporated in a resistively-heated crucible. Since Co undergoes a magnetic transition at approximately 1100°C, it was found to be incompatible with PIB evaporation. The deposition rates were selected such that the flux of the Co and Ge atoms arriving at the substrate was 1:2. The deposition rates for the Co and Ge were approximately 0.5 Å/s and 2.1 Å/s, respectively. The base pressure was 1×10^{-7} torr, and all films were grown to a thickness of 1500 Å under a vacuum of 5×10^{-7} torr.

After growth, the samples were characterized using a Scintag X-ray diffraction system 2000. The phases and grain orientations present in the film were determined by 2θ scans, while the azimuthal orientations of the grains relative to the substrate were determined using pole figure analysis.

OBSERVATIONS

The experimental parameter space was explored by holding the substrate deposition temperature constant and performing several depositions, each with a different ion energy. The temperature range varied from 100° to 490°C. Analysis of the deposition phases showed that the $CoGe_2$ phase formed most readily at a substrate temperature of 280°C, regardless of ion energy. At very low substrate temperatures (≤200°C), only a small degree of crystallinity in the films was observed. In addition, at a substrate temperature of 490°C, the film was found to possess little crystallinity, however, very small droplets of a shiny liquid formed on the sample surface. This was assumed to be elemental Ga, which is known to diffuse out of the GaAs lattice at a temperature of 550°C (ref 17). Depositions at 360°C formed almost no $CoGe_2$, but were characterized by multiple 2θ peaks. Phase identification here was not possible, due to the coincidence of several possible phases of different materials at nearly the same 2θ angle. Some possibilities at 32.2° include As_2O_3(140) and As_2O_4(220). At 42.9° β-Ga_2O_3(-211), $Co_{.62}Ga_{.10}Ge_{.28}$(112), As_2O_3(221), and As_2O_4(230) are all possibilities. Finally, the peak at 46.2° could consist of $CoGe_2$(204) and/or CoGe(112). These observations are summarized in Figure 1, which shows the 2θ scans of samples grown with approximately 1100 eV ions and a substrate temperature ranging between 100° and 490°C.

The films that displayed the $CoGe_2$ phase were examined with pole figure techniques to determine any preferred orientation present in the films. In the pole figure analysis, the 2θ angle is fixed for Bragg diffraction of a plane of interest. The sample is then tilted incrementally from 0° to 80° while rotating 360° about each tilt increment. The result is a stereogram in which the poles (or normals) from each plane in a family with common d-spacing are revealed. If the stereogram contains rings of intensity, this means the planes are randomly oriented in the film, while spots of intensity (poles) give the exact tilt and azimuthal angles of the planes being examined. The relation between the pole locations in the film and the substrate allow for the determination of the orientation of the film relative to the substrate.

The films deposited at approximately 280°C and with 1100 eV Ge^+ ions display a very tight epitaxial arrangement. The epitaxial arrangement of such a sample is shown in the stereograms of Figure 2. The film stereogram (Figure 2a) shows four (111) poles at a tilt angle of 69.7°. In a single crystal of $CoGe_2$, there are four equivalent (111) poles in the (001) projection, and the angle between the (001) and (111) planes in a tetragonal crystal is 69.7° with the (111) planes exhibiting fourfold symmetry about the [001] direction. In the substrate projection

(Figure 2b), four GaAs(111) poles are observed at a tilt angle of 54.7° (the angle between the GaAs(100) and (111) planes) and are oriented at exactly the same azimuthal angle as the $CoGe_2$(111) poles. Thus, the orientation of the film and substrate coincides, and the epitaxial relationship of the film/substrate system is revealed.

Current-voltage measurements were performed on 4.42×10^{-3} cm^2 contacts grown at the ideal conditions for epitaxial growth, and the structure was found to exhibit ohmic behavior. Contacts grown at substrate temperatures above or below the approximately ideal substrate temperature of 300°C were found to be rectifying. Four current-voltage curves of these observations are shown in Figure 3. At the present time, the underlying mechanisms for these behaviors are not understood.

The system in Figure 2 is believed to be in a parallel epitaxial arrangement of $CoGe_2$ (001)/GaAs(100). Interestingly, films deposited at 280°C with lower ion energies displayed a different, nonparallel epitaxial arrangement. The exact nature of the epitaxy is still not clear. This same arrangement is also found for those films deposited with a lower substrate temperature of 200°C and an ion energy near 1100 eV. Lowering the substrate temperature or reducing ion energy both seem to produce a different structure for the film. We believe that Ge^+ ions in the evaporant stream increase the surface mobility, provide additional energy to the growth front, sputter away light impurities (refs 18-20), and also suppress three-dimensional island growth by increasing the density of nucleation sites (ref 21), thus facilitating high-quality epitaxial growth.

Atomic force microscopy (SFM) analysis showed that the surface of the epitaxially grown films is rough, with a root mean square roughness of 400 Å for a 1500 Å thick film. It is possible that preferential faceting is responsible for the roughness. However, the film is found to be continuous with no observable grain boundaries. Due to the high intensity of the $CoGe_2$(004) and (008) peaks in the 2θ scan and the fact that the (111) poles in the stereogram are remarkably tight (as narrow as the substrate poles), the film is believed to be almost completely single crystalline.

CONCLUSION

In conclusion, it was found that high quality heteroepitaxial $CoGe_2$(001)/GaAs(100) samples could be grown with a remarkably tight texture by a proper choice of substrate temperature and ion energy using the PIB deposition technique. Contacts deposited at this condition appeared to be ohmic at low voltages. The epitaxy was achieved under a conventional vacuum using minimal substrate surface preparation. Epitaxial $CoGe_2$ films have the potential to produce stable contacts to *n*-GaAs. Using the PIB system, epitaxial $CoGe_2$ may be a viable alternative to the metallization of *n*-GaAs.

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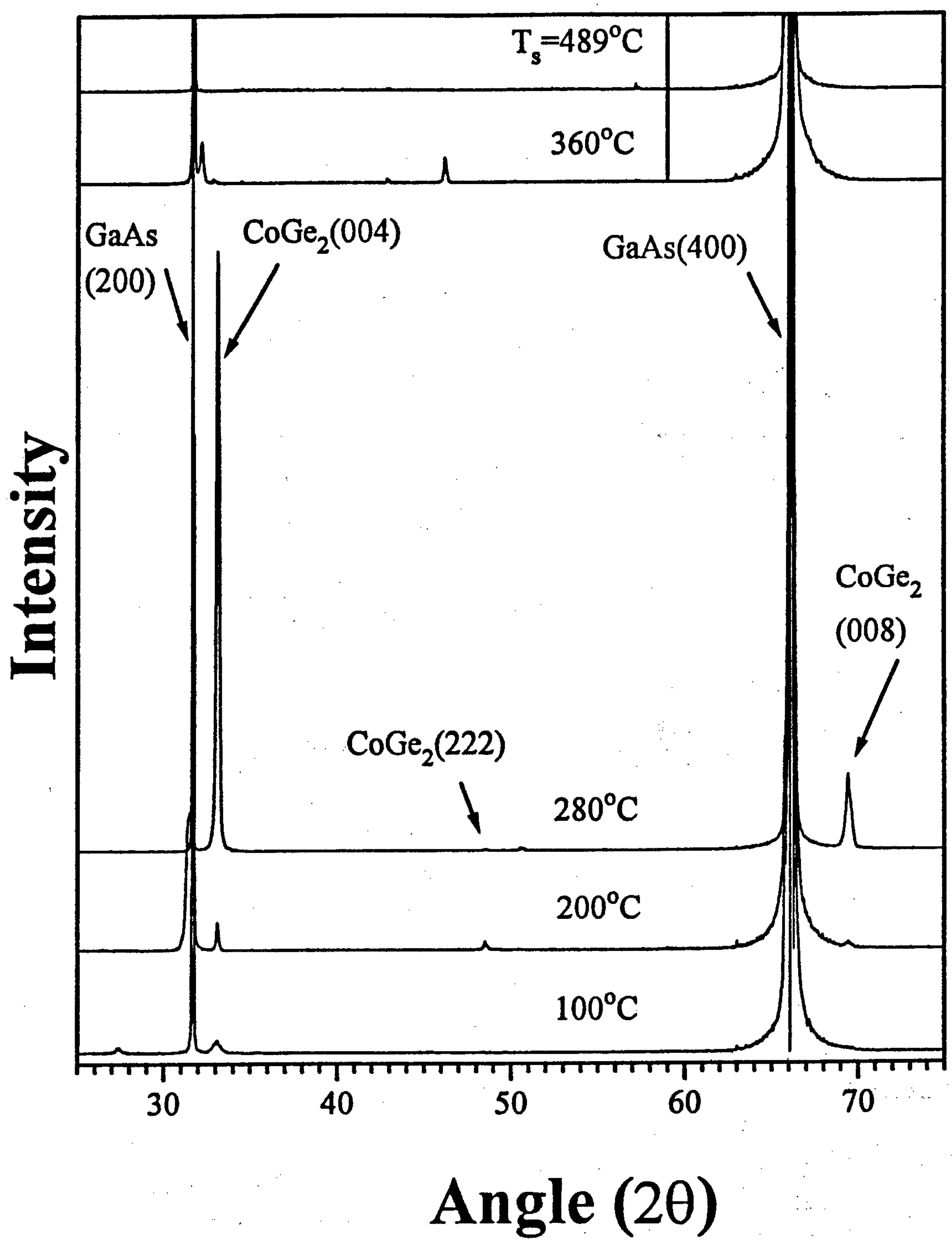
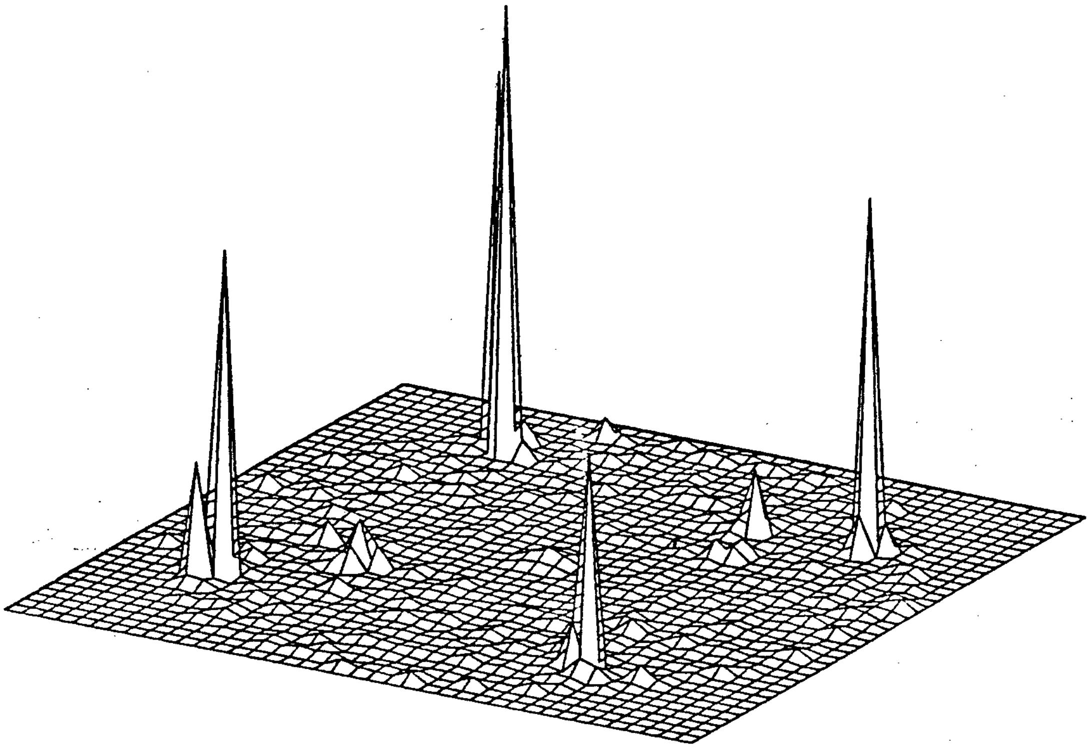
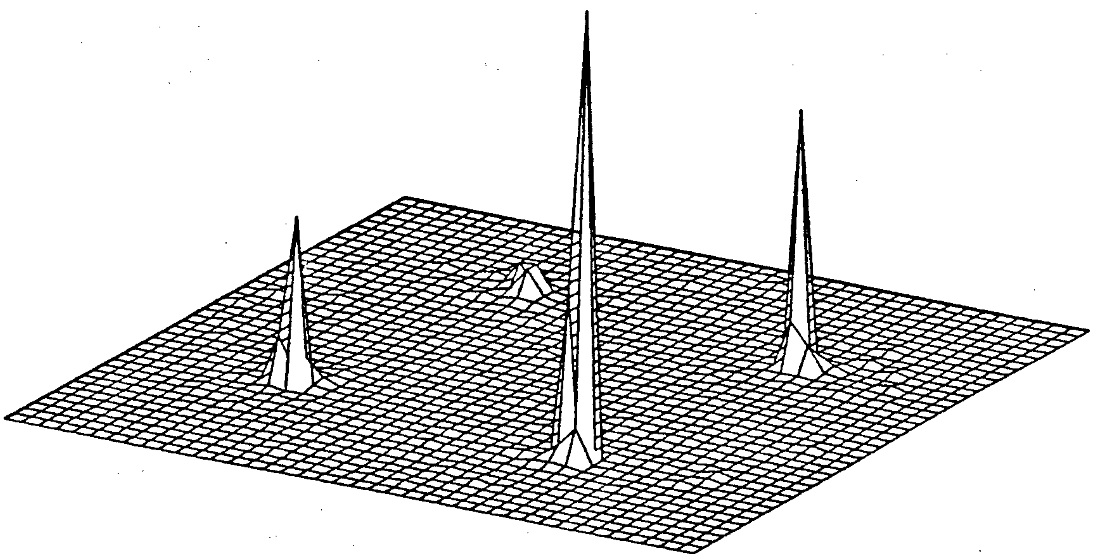


Figure 1. 2θ scans of samples grown at various substrate temperatures with Ge^+ ion energies of approximately 1100 eV. The curves show the temperature dependence of Co-Ge phase formation. A substrate temperature of 280°C yields the highest degree of $CoGe_2$(001).



2a. The (111) poles from the $CoGe_2$ film. The peaks display fourfold symmetry at a tilt angle of 69.7°, revealing the azimuthal orientation of the $CoGe_2$ lattice.



2b. The (111) planes of the GaAs substrate. The azimuthal orientations of the CoGe2(111) and GaAs(111) poles reveal their epitaxial relationship.

Figure 2. Stereograms of the $CoGe_2$(001)/GaAs(100) epitaxial system obtained with 1100 eV Ge^+ ions and a substrate temperature during deposition of 280°C.

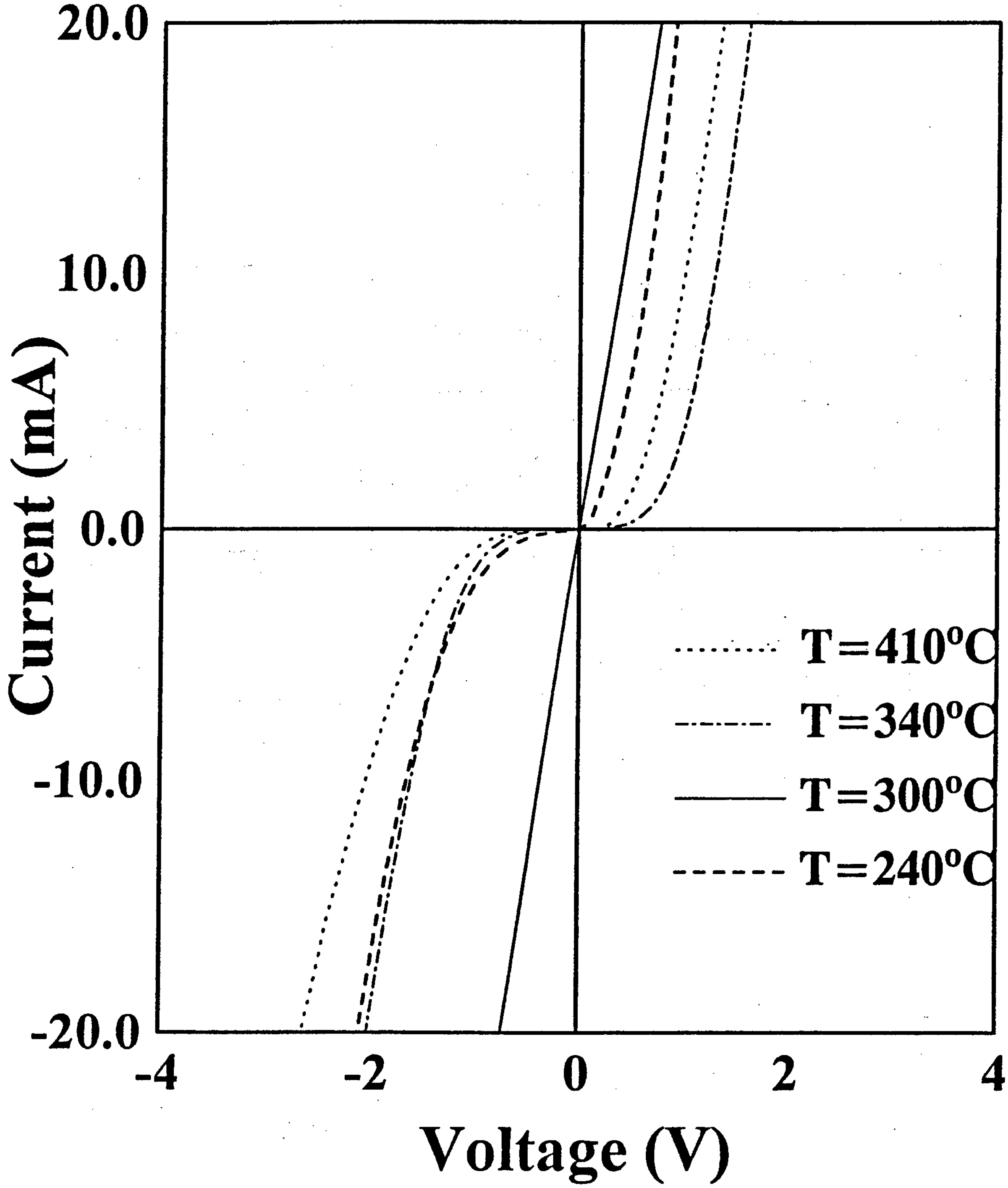


Figure 3. Current-voltage characteristics of the Co-Ge/GaAs contact system grown at various substrate temperatures.

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