Oscillations in the optical characteristics of the growth surface on Ge films during molecular beam epitaxy

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Measurements by automatic reflection ellipsometry reveal a new effect: oscillations in the optical characteristics of the surface layer during molecular beam epitaxy of germanium. The oscillation period is equal to the time required for the formation of a layer two atoms thick.

Periodic changes in the intensity of reflections during reflection high-energy electron diffraction (RHEED) at the surface of single-crystal films during their growth by molecular beam epitaxy (MBE) were observed in Refs. 1–3. This effect is presently linked with a periodic change in the surface relief during growth by a two-dimensional mechanism, because of an alternation of nucleation and intergrowth of two-dimensional growth regions.

In this letter we report the observation by automatic ellipsometry of oscillatory changes in the optical characteristics of the growth surface during MBE of germanium.

The experiments are carried out on the MBE apparatus of Ref. 4, fitted with an electron gun for RHEED and with an automatic laser ellipsometer (wavelength of 632.8 nm). After the GaAs substrate, with the orientation 100 ± 20′, is cleaned by heating in ultrahigh vacuum (10^{-7}–10^{-8} Pa), a Ge layer 200 nm thick is grown. The optical absorption in such a layer is strong enough to eliminate any significant effect of the substrate on the polarization of the reflected light. Before each experiment on the observation of oscillation, we carry out an annealing at $T \cong 500\ ^\circ\text{C}$ for 10 min in order

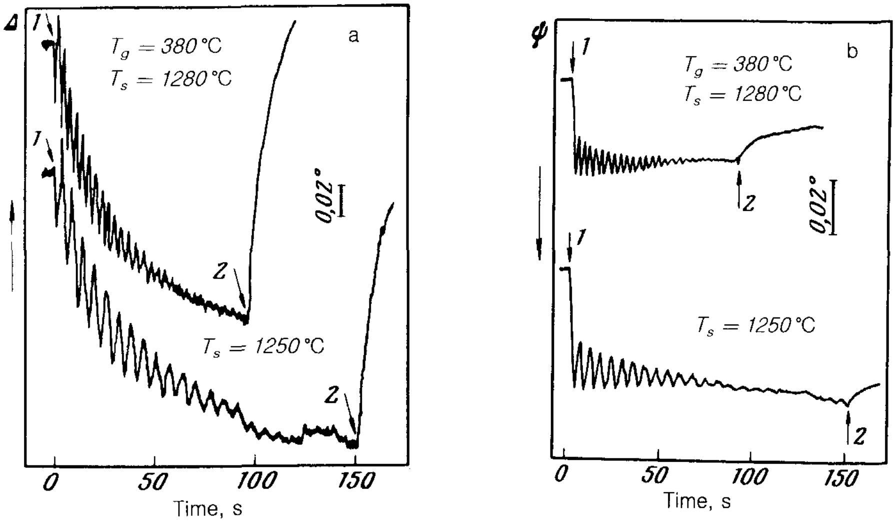

FIG. 1. Time evolution of the ellipsometric angles (a) Δ and (b) Ψ during the growth. 1—Beginning of the growth; 2—end of the growth.

to restore the original optical properties of the surface. The desired growth temperature T_g is then established, and the film growth is begun. During the growth, we measure the changes in the ellipsometric angles or the intensity of reflections on the RHEED pattern. The ellipsometric angles Δ and Ψ vary periodically during the growth (Fig. 1). An increase in the growth rate due to an increase in the source temperature (T_s) shortens the oscillation period. From the interferometric measurements of the height of the film-substrate step after a long growth time and from the data in Fig. 1 we can determine the change in the film thickness per period of the oscillations in Δ and Ψ. For both values of T_s, it turns out to be $a/2$ ($\pm 1.5\%$), where $a = 3.56$ nm is the germanium lattice constant. The monotonic decrease in the angle Δ can be attributed to a heating of the sample by the radiation from the molecular

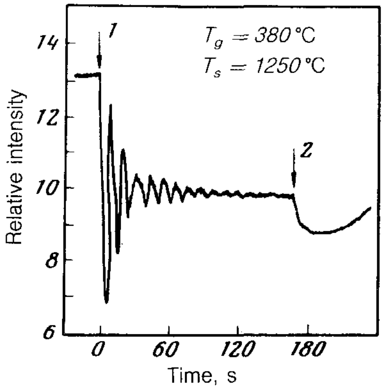

FIG. 2. Time evolution of the intensity of the (00) reflection during the growth. 1—Beginning of the growth; 2—end of the growth.

source, in agreement with the known temperature dependence of Δ for germanium with an atomically clean surface. The damping of the oscillations which is evident on the curves apparently results from a relaxation to a steady-state relief in the course of the growth.

The intensities of the reflections on the RHEED pattern also oscillate during the growth (Fig. 2). Comparing Figs. 1 and 2, and taking into account the difference in the growth rates in the diffraction and ellipsometric measurements (due to different distances from the source of the Ge vapor to the substrate), we find that the oscillation period during the RHEED is also equal to the growth time of a layer of thickness $a/2$. The complete matching of conditions (the substrate temperature and the growth rate) under which the oscillations in the ellipsometric angles and the electron diffraction intensity are observed is evidence that these phenomena have a common origin.

The oscillations in the optical characteristics of the surface can be utilized to study surface reactions which involve the formation of nucleating two-dimensional growth regions (the growth of crystals, their dissolution, their oxidation, etc.) by the method of automatic ellipsometry under conditions such that RHEED cannot be used (if the material undergoes changes during bombardment by the electron beam, if the process is carried out in a medium which is dense for an electron beam, if the insulating film increases in size, etc.

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