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Homoepitaxial growth rate measurement using in situ reflectance anisotropy spectroscopy

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Abstract

We present a novel method to measure growth rates during homoepitaxy using reflectance anisotropy spectroscopy (RAS). We have grown Si and Zn doped as well as undoped GaAs and InP layers in MOVPE. The RAS signal at photon energies near the fundamental band gap shows an oscillatory behavior (Fabry–Pérot-like oscillations) during growth whenever the doping concentration has been changed. The period of these oscillations can be directly related to the growth rate via the length of the optical path through the growing layer, while the amplitude of the oscillations correlates to the doping level contrast at the interface. We attribute these oscillations to the linear electro-optic effect (LEO) at the interface between two differently doped layers.

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1. Introduction

Real-time measurements of the growth rate during III–V homoepitaxy (e.g. GaAs on GaAs, InP on InP) are still an unsolved problem in epitaxial growth. Techniques like reflection high-energy electron diffraction (RHEED) and reflectance anisotropy spectroscopy (RAS) monolayer growth oscillations can determine the growth rate in the 2D island growth mode [1,2]. Unfortunately, this applies only to certain materials in a relatively narrow window of sometimes unfavorable growth conditions (lower temperatures, certain growth rates). Moreover, monolayer oscillations can only measure the growth of the first few nanometers. In this work, we demonstrate growth rate measurements by RAS during homoepitaxial growth of layers that have sufficiently high doping level contrast.

The fact that doping changes the shape of RAS spectra is known since the early 90s. The sensitivity of the RAS signal to the doping concentration can be explained by the linear electro-optic effect (LEO) which describes the change of optical constants via the electric field generated by the free carriers of a space charge layer near an interface [3–6]. However, we report for the first time an oscillatory behavior of the RAS signal near the fundamental band gap when the doping concentration has been changed during growth. In reflectometry, an oscillating signal for extremely high p-doping of GaAs with carbon concentrations in the $10^{19}-10^{20}\,\mathrm{cm}^{-3}$ range has been reported [7,8]. The origin of such oscillations was attributed to the change of the refractive index due to the dopant-induced chemical/lattice parameter change.

2. Experimental procedure

The growth experiments were performed in a horizontal double-wall MOVPE reactor with low-strain optical windows. The total pressure was 100 mbar, hydrogen was used as carrier gas. The group V precursors were arsine (AsH_3) and phosphine (PH_3), the group III precursors were trimethylgallium (TMGa), triethylgallium (TEGa), and trimethylindium (TMIn). For doping, 100 ppm diluted

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silane (SiH_4) and a dimethylzinc-adduct (DMZn) were used as dopant sources. A multichannel RAS setup was used to record RAS transients at multiple wavelengths simultaneously, together with a conventional RAS system [9]. The free carrier concentration of the layers was analyzed by C–V-profiling.

3. Results and discussion

The RAS signal is defined as

$$\frac{\Delta r}{\langle r\rangle} = \frac{r_{[\bar{1}\,1\,0]} - r_{[1\,1\,0]}}{\frac{1}{2}(r_{[\bar{1}\,1\,0]} + r_{[1\,1\,0]})} \tag{1}$$

where $\Delta r = r_{[\bar{1}\,1\,0]} - r_{[1\,1\,0]}$ is the anisotropy in reflectance and $\langle r\rangle$ is the isotropic reflectance [10]. During growth of layers with different dopant concentration we observe clear oscillations in $\Delta r/\langle r\rangle$ (Fig. 1), but not in the reflectance signal $\langle r\rangle$. These oscillations occur most pronounced for GaAs but have been observed for InP, too.

We use a multichannel RAS setup to measure the RAS signal at multiple wavelengths simultaneously [9]. Fig. 1 shows reflectance $\langle r\rangle$ (upper part) and RAS (lower part) transients recorded simultaneously during growth of undoped GaAs on a doped GaAs:Si substrate ($5\times10^{18}\,\mathrm{cm}^{-3}$). The RAS transients show a clear oscillatory behavior which is not visible in the reflectance signal $\langle r\rangle$. For shorter wavelengths, corresponding to smaller penetration depths of the light, the oscillations in the RAS transients damp out faster. In this aspect, the RAS oscillations behave similarly to Fabry–Pérot interference oscillations. On the other hand, the features in the reflectance transients are similar at all photon energies and thus are most likely due to noise of the light source and small variations of the sample position or similar external effects.

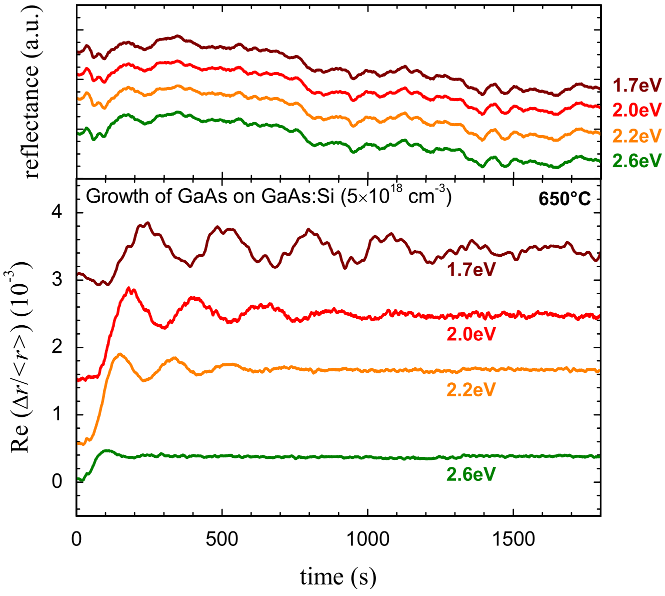

Fig. 1. Reflectance $\langle r\rangle$ and RAS transients recorded simultaneously during growth of GaAs on GaAs:Si ($5\times10^{18}\,\mathrm{cm}^{-3}$). The transients are shifted vertically for better visibility.

Fig. 2(a) shows a RAS transient recorded at 1.6 eV during growth of a five-layer stack of GaAs and GaAs:Si on top of a GaAs:Si substrate ($5\times10^{18}\,\mathrm{cm}^{-3}$). Layers no. 1 and no. 5 are nominally undoped, whereas in between the doping concentration decreases from layer no. 2 to no. 4. The oscillation amplitude is apparently not related to the doping concentration, but related to the difference in doping concentration between the layers. This can be easily recognized by comparing the amplitude during growth of the two undoped layers, no.1 and no. 5. The amplitude of the first (undoped) layer no. 1 is much higher than that of the last (also undoped) layer no. 5, because the difference in the doping concentration is higher for layer no. 1.

In Fig. 2(b) the growth of GaAs and GaAs:Zn is monitored at 1.48 eV. The substrate was GaAs:Zn ($8\times10^{18}\,\mathrm{cm}^{-3}$). Comparing Fig. 2(a) and (b) shows that the mean value of the oscillations, the baseline, correlates with the doping of the growing material: p-type doping leads to a positive and n-type doping to a negative offset. This effect has also been observed in the RAS spectra of doped samples [6].

The RAS transients can be fitted by an exponentially damped cosine function to determine the baseline, the amplitude, the period and the damping. From the period t_p the growth rate G can be calculated using the equation for Fabry–Pérot interference oscillations

$$G = \frac{\lambda}{2nt_\mathrm{p}}, \tag{2}$$

where λ is the wavelength of the probing light and n is the refractive index of the growing layer at growth temperature. For G values between 0.317 and 0.331 nm/s were obtained for GaAs:Si ($n_{1.6\,\mathrm{eV}} = 3.9443$). For the p-type sample ($n_{1.48\,\mathrm{eV}} = 3.8738$), the growth rates were 0.502 (layer 1) and 0.479 nm/s (layer 2). These values agree well with the growth rate obtained ex situ and in situ from monolayer growth oscillations (at lower temperature).

To analyze the effect of doping on the amplitude of the oscillation, we define a doping contrast C_{i+1} between layer i and layer $i+1$ as

$$C_{i+1} = \log\frac{N_{i+1}}{N_i} = \log N_{i+1} - \log N_i, \tag{3}$$

where N_i is the respective dopant concentration of layer i. The definition was chosen this way because the RAS signal offset due to doping is proportional to the logarithm of the dopant concentration for moderate doping levels [6].

Fig. 3 shows the magnitude of the oscillation amplitude as a function of the absolute value of the doping contrast $\log(N_{i+1}/N_i)$ within the GaAs:Si layer stack. The amplitude is linear for larger doping contrasts (layers no. 1, 2, and 5) but saturates for doping contrasts below 1 (layers no. 3 and 4). A similar dependence was found for the change of RAS spectra as a function of the logarithm of the dopant concentration [6]. This indicates towards a similar