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PERIODIC FLUX INTERRUPTION AND SUSTAINED TWO-DIMENSIONAL GROWTH FOR MOLECULAR BEAM EPITAXY

Indexing terms: Semiconductor devices and materials, Semiconductor growth, Epitaxy and epitaxial growth, GaAs

Periodic interruption of Ga flux during MBE growth of GaAs has been used to achieve sustained two-dimensional layer-by-layer growth. RHEED intensity oscillation for extended growth shows no degradation in the oscillation amplitude, indicating an atomically smooth growth front throughout the growth.

Molecular beam epitaxy (MBE) has its advantages over other epitaxial growth techniques by having the atoms (or molecules) deposited nearly (atomic) layer-by-layer, resulting in a very smooth growth surface. This growth behaviour can be best seen by the RHEED (reflection high energy electron diffraction) intensity oscillation during growth. Each oscillation period corresponds to the completion of an atomic layer. The amplitude of oscillation, however, drops steadily as the growth proceeds. The number of oscillations that is observable is usually below 100. The decline of the oscillation intensity is due to the deterioration of the growth front during a continuous growth.

It has been reported that the smoothness of the growth front has a great impact on the material quality.[1] For III-V compound semiconductor growth, interruption of the group III atom flux has been shown to be useful to smooth out the growth surface.[2] Growth interruption has been used to improve the quality of devices such as quantum wells and resonant tunnelling diodes.[3,4]

In this letter we report a simple technique to achieve sustained two-dimensional layer-by-layer growth using periodic growth interruption. Unlimited number of atomically smooth layers can be grown and can be easily observed with RHEED oscillation.

The growth was performed on a (001)-oriented GaAs substrate. The growth temperature was 570°C. After oxide desorption, a 1000 Å-thick GaAs layer was first grown under As stabilised conditions. The growth rate was 0·22 monolayer/s (or 4·5 s/ml). The beam-equivalent pressure ratio of As_4/Ga was 18. The Ga shutter was then closed and the sample idled with only the As shutter open for 10 min to ensure a smooth starting surface. The growth was started and the Ga shutter was programmed with a periodic on/off sequence of 4·5 s shutter open time and followed by 5 s close time. During the 4·5 s shutter open time, a complete layer of GaAs was deposited. In the subsequent 5 s shutter close time, the surface is smoothed out via migration of adatoms. The surface smoothness was monitored by RHEED along the [100] azimuth. Intensity oscillation of the specular spot was recorded during growth. It was found that the recovery of the RHEED intensity was very fast after the completion of a single layer. A 5 s interruption was enough to enable the intensity to reach the 85% level of the original intensity before growth. This is because the surface was still very smooth after the first layer growth, and it does not need a long time to recover. The recovery time is much shorter than that needed after a long continuous growth, which often requires tens of seconds.

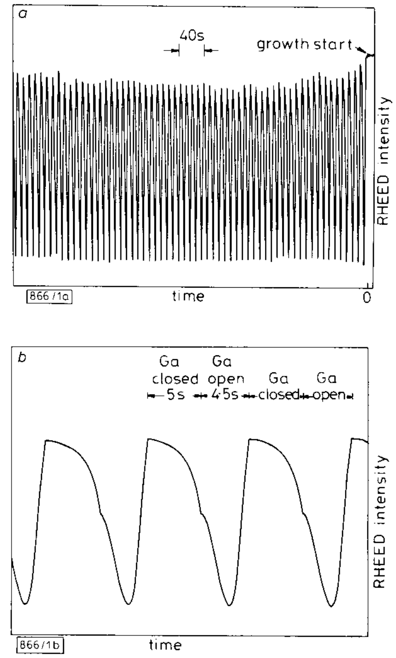

Fig. 1

a RHEED intensity oscillation trace of growth with periodic interruption of Ga flux
b Expanded oscillation pattern of Fig. 1*a*
Ga shutter has periodic on/off sequence with 4·5 s shutter open time and 5 s shutter close time

By switching the Ga shutter on and off with the time sequence described above, a sustained two-dimensional layer-by-layer growth can be achieved. Fig. 1*a* shows the RHEED intensity oscillation trace during a growth run. A steady oscillation pattern is observed and there is no degradation in the oscillation amplitude. The intensity change during each layer growth can be seen in the expanded trace shown in Fig. 1*b*. During the first 4·5 s, when the Ga shutter is open, the intensity first drops and then comes back to a maximum at the end of this period. For the next 5 s the Ga shutter is closed and the intensity recovers to the original level of the previous period. The sequence is repeated and a steady-state layer-by-layer growth is obtained. To compare this growth technique with the conventional growth method, we show the RHEED oscillation pattern of a growth run without interruption in Fig. 2 (other growth conditions were kept the same as before). A

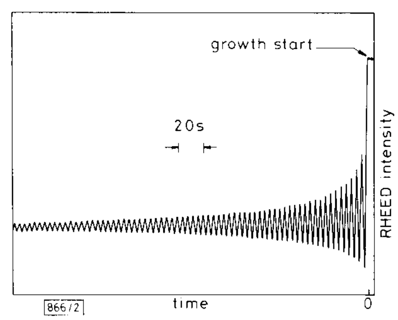

Fig. 2 *RHEED intensity oscillation of GaAs growth without interruption of Ga flux*

Other growth conditions are same as those used in Fig. 1*a* clear difference between the two is seen in the RHEED oscillation patterns. For the conventional growth, the amplitude decreases rapidly, indicating deteriorating growth front. For the periodic on/off operation of the Ga shutter, the layer smoothness is maintained throughout the growth.

Shorter growth interrruption times have also been tried. Figs. 3*a* and *b* are the RHEED oscillation traces of the growths with 3 and 1 interruptions, respectively. The shutter open period was kept at 4·5 s as before. Although steady oscillation can be obtained after a few periods of oscillation, the amplitudes are smaller than that with 5 s interruption. For the growth with 1 s interruption, the oscillation pattern exhibits irregular shapes (see Fig. 3*b*). This is probably because the growth surface is not the same for each growth period after such a short interruption time. The choice of the interruption time depends on the growth conditions, such as substrate temperature and As flux. Different surface mobilities resulting from different conditions will dictate the amount of time required for the interruption. It should also be pointed out that the recovery time depends on the percentage of the Ga coverage on the surface. It is important to programme the shutter sequence so that the shutter closes right at the completion of an atomic layer. Otherwise, a much longer interruption time is needed and steady two-dimensional growth is difficult to obtain.

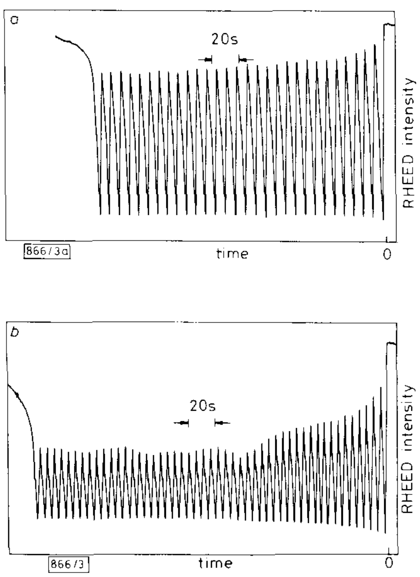

Fig. 3 *RHEED intensity oscillation of growth run with (a) 3 s interruption and (b) 1 s interruption for each layer*

Shutter open time was fixed at 4·5 s for each layer

In conclusion, sustained two-dimensional layer-by-layer growth of GaAs has been achieved using periodic interruption of the Ga flux. RHEED intensity oscillation indicates that a smooth surface for each layer can be maintained throughout the growth.

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TUNABLE CW LASING AROUND 0·82, 1·48, 1·88 AND 2·35 μm IN THULIUM-DOPED FLUOROZIRCONATE FIBRE

Indexing terms: Optical fibres, Lasers and laser applications, Doping

Tunable CW operation of a thulium-doped fluorozirconate fibre laser around 0·82 μm, 1·48 μm, 1·88 μm and 2·35 μm is reported. The fibre is single mode above 1·7 μm. Laser dynamics and competition or collaboration between these wavelengths are examined.

Introduction: Pulsed and CW lasing has been reported in Tm^{3+}-doped fluorozirconate fibres at 2·3 μm[1,2] and at 1·9 μm in silica fibres.[3] We report in this letter on tunable continuous-wave oscillation in Tm^{3+}-doped fluorozirconate fibres. The experimental set-up is the same one we have already used to obtain tunable CW emission around 0·85 μm, 0·98 μm (tunability 23 nm), 1·55 μm (tunability 32 nm) and 2·71 μm (tunability 70 nm) in erbium-doped fluorozirconate fibres.[4,5] A glass prism is inserted in the cavity to spatially separate pump and signal beams, and a rotating high reflectivity mirror is used for wavelength tuning. Additional devices, such as a Fabry–Perot étalon or a *Q*-switch, can be inserted in the signal path. For experiments requiring a cavity response independent of wavelength, a mirror is inserted between the prism and the fibre input.

The fibre we have used in these experiments is of classical ZBLAN composition, with a thulium concentration of 1250 ppm weight, corresponding to 2.0×10^{20} atoms/cm³. It has a core diameter $2a = 7.2$ μm and a refractive index difference between core and cladding $\Delta n = 11.6 \times 10^{-3}$, yielding a cutoff wavelength of about 1·7 μm. For all fluorescence and lasing experiments reported below, we have used the same 150 cm-long piece of fibre and a pump wavelength of 676·4 nm.

The energy levels of Tm^{3+} in fluorozirconate glasses are shown in Fig. 1,[6,7] together with measured or predicted life-

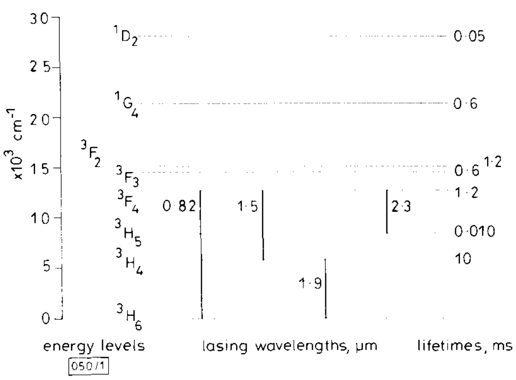

Fig. 1 *Energy levels of Tm^{3+} in fluoride glasses*

Transitions studied are labelled