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A NEW TECHNIQUE FOR THE GROWTH OF COMPOSITIONALLY GRADED LAYERS BY OMCVD FOR NOVEL DEVICE STRUCTURES

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The ability to compositionally grade epitaxial semiconductor layers in a desired fashion is important for the fabrication of modern semiconductor devices and structures for device physics studies. Such grading has traditionally been achieved, in chemical vapor deposition, by careful ramping of the mass flow controllers. In this paper, we demonstrate a more flexible technique for achieving compositional grading using a fast switching manifold which allows us to deposit ultra-thin layers of any desired composition. The technique was used to fabricate a hot electron transistor in the AlGaAs alloy system consisting of two electrically ideal triangular potential barriers.

1. Introduction

Epitaxial layers with compositional grading in the growth direction are essential for many semiconductor devices of current interest such as heterojunction bipolar transistors, hot electron transistors, lasers, and photodetectors. In addition, such structures can be used in the study of fundamental phenomena in solid state physics. Since many of the structures of interest require thin layers, abrupt interfaces and compositional grading over small thicknesses (typically 100–200 Å), they have been grown, almost exclusively, by molecular beam epitaxy (MBE). The lack of high throughput and the presence of a high density of oval defects have motivated a large number of laboratories to examine organometallic chemical vapor deposition (OMCVD) as an alternative to MBE. The ability to grow state-of-the-art lasers by OMCVD has been demonstrated [1,2]. More recently high transconductance modulation doped transistors showing no $I-V$ collapse, in the dark at low temperatures, have been grown by OMCVD [3].

2. Experimental

The conventional approach to achieve compositional grading in OMCVD has been by ramping the appropriate flow controllers. This technique has many disadvantages such as the finite response time of the flow controllers which places a minimum thickness limit over which grading can be achieved, the necessity for many calibration runs for composition and growth rate across the entire composition range of interest and the difficulty of ensuring that the epitaxial layer grown is lattice matched to the substrate over the entire ramping range. An alternative to this "analog" approach is a "digital" one where alternate layers of appropriate thickness are grown with compositions corresponding to the low and high end points on the compositional profile. A digital approach has been used in MBE for the growth of AlGaAs layers with a linear [4] or a parabolic [5] Al composition profile by pulsing the Al beam. The greater flexibility of this approach, as compared to the analog technique wherein the Al composition is changed by varying the Al effusion cell temperature, has been clearly demonstrated [4–6]. The digital technique can be implemented in OMCVD by using a fast switching manifold such as the one reported by Griffiths et al. [7]. We examine this novel approach and present experimental data for graded AlGaAs–GaAs heterojunctions below.

In order to use the digital technique to achieve compositional grading, we must first define growth rates for the low and high end points on the composition profile. It is necessary to obtain calibrations of growth rate and composition for these end points only. We then define a thickness period, t, which is sufficiently small and divide it into n equal parts. By alternately growing material corresponding to the low end of the composition profile of thickness kt/n and the high end of the composition profile of thickness $(n-k)t/n$, where k is an integer having a value between 0 and n, we achieve compositional grading. The slope of the composition profile can be changed by changing n. However, a better approximation to a continuous grading is achieved by choosing a sufficiently large value of n and then changing the number of times one repeats a thickness period with a specific value of k to obtain the required slope.

Lattice matching is automatically ensured over the entire composition range provided that the end point compositions are lattice matched and there is no intermixing of the layers. When there is intermixing, as may be expected if the layers are sufficiently thin, a small mismatch will occur due to the slightly non-linear dependence of the intermediate alloy compositions on the lattice constant needed for lattice matching. This can be compensated for, if necessary, by introducing into the reactor an additional flow (or flows) for predetermined times using the fast switching manifold.

3. Results

As an example of the "digital" technique, we have grown AlGaAs/GaAs layers having an Al composition profile shown in fig. 1. In order to obtain this profile, we established a growth rate of 5 Å/s for both the GaAs and $Al_{0.3}Ga_{0.7}As$ layers having a thickness period of 10 Å. This thickness period was divided into 10 equal parts ($n = 10$); k was varied between 0 and 10. Slopes 1 and 4 were obtained by repeating each k value 3 times whereas each k was repeated only once for slopes 2 and 3. A SIMS profile of the layers grown is shown in fig. 2 and it can be clearly seen that the desired profile was achieved. The flat top between slopes 3 and 4 and the peak between slopes 1 and 2 are not clearly resolved due to the limited resolution of the SIMS technique. The slight non-lin-

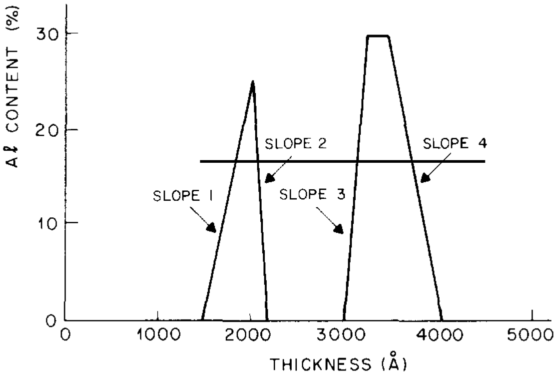

Fig. 1. A sketch of the desired Al composition profile.

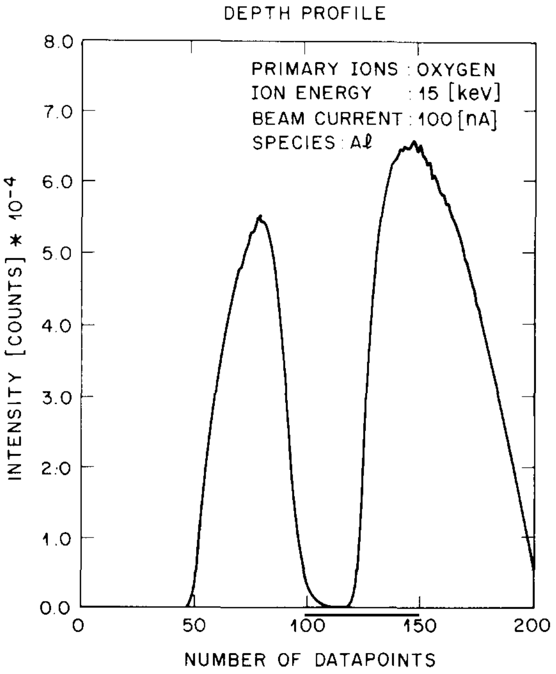

Fig. 2. SIMS profile of epitaxial layers grown to duplicate the Al composition profile in fig. 1.

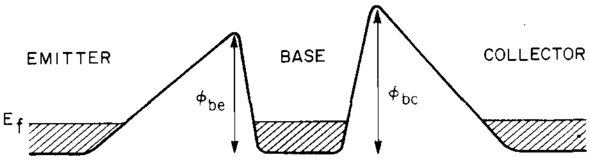

Fig. 3. Schematic diagram showing the conduction band edge of a hot electron transistor.

earity in the ramping of the Al profile occurs due to the decrease in sputtering rate with increasing Al content.

We have shown using spectroscopic ellipsometry [8] that the transition region between GaAs and AlGaAs is ≤ 5 Å. However, it is unlikely that we are achieving abrupt transition between GaAs and $Al_{0.3}Ga_{0.7}As$ when we attempt to grow layers thinner than 5 Å. Therefore, by pulsing rapidly between GaAs and $Al_{0.3}Ga_{0.7}As$, we are achieving some intermediate composition determined by the value of k, and thus obtain a smooth grading. Although we have demonstrated only linear grading, it is obviously possible to extend this technique to obtain non-linear Al composition grading and to tailor n- and p-type doping profiles.

The structure described above was used to fabricate a hot electron transistor. A schematic diagram of the energy band structure is shown in fig. 3 and consists of three degenerate ($n \approx 1 \times 10^{18}$ cm^{-3}) GaAs regions separated by two undoped ($n \approx 2 \times 10^{16}$ cm^{-3}) digitally graded AlGaAs potential barriers. The potential barrier forming the hot electron injector was designed to inject electrons into the base region with an excess energy above the conduction band minimum of 0.19 eV. This eliminates the possibility of intervalley scattering which would occur if the electrons were injected with an energy in excess of ≈ 0.33 eV. The potential barrier (ϕ_{bc}) forming the collector was grown with a higher Al concentration enabling us to analyze the hot electrons injected into the base using the technique of hot electron spectroscopy [9]. The wafer was etched using standard chemical etching techniques to form a two level mesa structure so that the three n^+ regions could be contacted individually with an evaporated Au–Sn alloy. The AlGaAs/GaAs diodes formed by this technique at the emitter-base and collector-base junctions have ideal behavior and only begin to deviate from it at high current levels when the contact resistance becomes important.

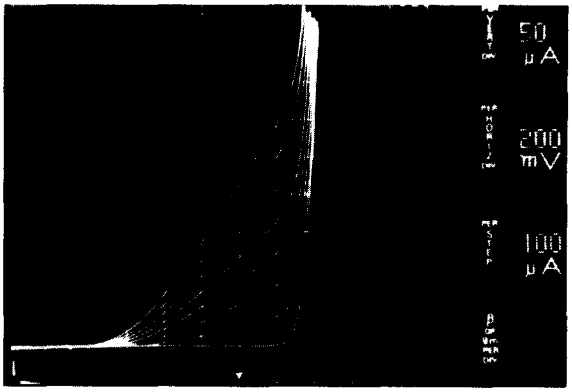

Fig. 4. $I-V$ characteristics of a typical hot electron transistor at 4.2 K. The emitter diameter was 100 μm.

With the base at ground potential, biasing the emitter negative causes thermal electrons to surmount the emitter-base barrier and subsequently gain kinetic energy ϕ_{be}. In this way a non-equilibrium electron distribution is injected into the base with nearly all its momentum peaked in a direction normal to the barrier plane. The resulting distribution after its interaction with the scattering mechanisms within the base region is analyzed using the second potential barrier. There are no electrons collected at biases between 0–0.4 V since no electrons have sufficient energy to surmount the barrier ϕ_{bc}. However, with increasing bias electrons are collected as can be seen from the steadily increasing collector current with base-collector voltage. The $I-V$ characteristic shown in fig. 4 are typical of the best quality GaAs planar doped barrier devices, indicating that devices, previously grown exclusively by molecular beam epitaxy, can now be fabricated by OMCVD using the digital grading technique.

4. Conclusions

We have shown, for the first time, that any complex compositionally graded profile can be obtained by OMCVD using a pulsing technique. Such compositionally graded structures are of great importance in improving the performance of heterojunction bipolar transistors, hot electron transistors, lasers, and photodetectors. The novel method demonstrated here enhances the attractiveness of OMCVD as a suitable technique for many devices of current interest.

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