Type-II gallium antimonide quantum dots and rings for optical devices

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Enhanced room-temperature photo- and electroluminescence of gallium antimonide quantum rings, formed by arsenic-induced dot-to-ring transitions show potential for optical device applications.

In recent years, type-II heterostructures have attracted great interest from researchers seeking to develop new semiconductor devices. Because electrons and holes are confined separately in type-II heterostructures, these carriers have longer storage times than in type-I heterostructures. However, the probability of optical recombination appears to be lower in type-II heterostructures compared to type-I, making them less suitable for optical devices such as LEDs. Therefore, previous studies of type-II nanostructures, such as gallium antimonide/gallium arsenide (GaSb/GaAs) quantum dots (QDs), have mostly focused on applying these structures to memory devices. As expected, the photo-luminescence (PL) of GaSb/GaAs QDs is most often only observed at low temperatures. Thus, there would seem to be no way to use type-II nanostructures for optical device applications. To challenge this assumption, we began by growing GaSb QDs and trying to optimize the growth conditions.

Since the lattice constant of GaSb is close to that of indium arsenide (InAs), we presumed that GaSb QDs could be prepared following a similar procedure to traditional InAs QDs. We therefore prepared two samples with 3s and 75s post-growth Sb soaking times, respectively, and studied the cross-sectional transmission electron microscopy images of the two samples: see Figure 1(a). In the sample with a 3s post growth Sb soaking time, the uncapped GaSb layer reveals a QD morphology. However, the embedded dots are transformed into quantum rings (QRs). In the sample with a 75s post-growth Sb soaking time, the dot morphology is maintained. Moreover, the PL intensity is simultaneously enhanced such that its PL spectrum can be observed: see Figure 1(b).

Figure 1. (a) Cross-sectional transmission electron microscopy images of gallium antimonide (GaSb) quantum dots (QDs) fabricated with 3s and 75s post-growth antimony (Sb) soaking times. (b) The 10K photoluminescence (PL) spectrum of the sample with 75s post-growth Sb soaking time. QR: Quantum ring. a.u.: Arbitrary units.

Based on the above observations, we have demonstrated room-temperature electroluminescence (EL) of a single-layer GaSb QD LED fabricated with a 120s post-growth antimony (Sb) soaking time. The results revealed that, with well-controlled GaSb/GaAs interfaces, intense luminescence is possible at room

Continued on next page
temperature, even for type-II QDs. Therefore, if we can further enhance the luminescence of the same type-II structure, the nanostructures would be suitable for optical devices, with their own unique characteristics.

Since the surface area of GaSb QRs exposed to GaAs is larger than that of GaSb QDs, is it possible that the greater number of electrons surrounding the structure would result in more intense luminescence if the QR growth was well controlled? To pursue this idea, we controlled the Sb/background As flux ratios during the post-growth Sb-soaking procedure and demonstrated that a high flux ratio results in a full dot morphology, whereas a low flux ratio produces a ring. These GaSb QRs seem to form by a different process than that usually employed to produce InAs QRs, namely, high-temperature annealing of InAs QDs partially capped with GaAs. Specifically, we attribute the GaSb QR formation to the intense As-for-Sb exchange on the GaAs/GaSb interfaces during the post-soaking procedure. As a result of the larger strain on the summits of the QDs, the replaced Sb atoms on the summits are then repelled from the dots and desorbed to the vacuum chamber. Therefore, with sufficient As, or long enough time, the QD structures gradually change to QR structures. The supporting evidence for this growth model is the similar diameters of the GaSb QDs and the QRs: see Figure 2(a). The result is a complete growth procedure for the preparation of either GaSb QDs or QRs by using molecular beam epitaxy (MBE).

The QR sample displays a PL intensity enhanced to ~20 times that of the QD sample: see Figure 2(b). Two possible mechanisms could be responsible for the PL intensity enhancement of the GaSb QRs. One is that less abrupt GaSb/GaAs interfaces result from the severe As-for-Sb exchange. As a result, the electron-hole wave function overlapping increases. The other possible mechanism is that there are more surrounding electron shells over the GaSb QRs, which results in the QRs having a higher optical recombination rate than the QDs.

Because of the enhanced PL intensity observed for the QR structure, we prepared a GaSb QR p-i-n diode to demonstrate the application of QR structures in LEDs. Room-temperature operation with a 0.7mA and 100MHz pulsed injection current produces a significant EL spectrum, with a peak at ~1.05eV (see Figure 3). The EL peaks observed at different injection currents are shown in the insert of the figure. The linear dependence of the EL peak on the third root of the injection currents confirms that the luminescence originates from type-II GaSb/GaAs QR structures.

In summary, we have developed a complete growth procedure for the preparation of either GaSb QDs or QRs by using MBE. Significant luminescence is observed for both QDs and QRs at room temperature, and more intense luminescence is observed for QRs. The results indicate that type-II GaSb QRs can be applied in LEDs. The longer carrier lifetime and tunable

Figure 2. (a) Scanning tunneling microscopy images of a single GaSb dot and ring. (b) 10K photoluminescence (PL) spectra and corresponding atomic force microscopy images of GaSb QDs and QRs.
emission wavelengths for different injection currents may be useful for the fabrication of wavelength-tunable LEDs in the near-infrared range. We aim to further enhance the luminescence intensity and extend the emission wavelength to 1.3µm (0.95eV) by inserting InGaAs capping layers. This may help to enhance electron accumulation and lower the conduction band edge near the GaSb QRs. We also hope to demonstrate type-II GaSb QR LEDs with compatible EL intensities and unique optical characteristics.

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**References**


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