GaSb-Based Type I Quantum-Well Light-Emitting Diode Addressable Array Operated at Wavelengths Up to 3.66 μm

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Abstract—Type I GaSb-based light-emitting diodes (LEDs) have been demonstrated while operating at room temperature at wavelengths up to 3.66 μm with approximately 200 μW of quasi-continuous-wave optical power. A mid-infrared 6 × 6 addressable array of Type I LEDs was also demonstrated.

Index Terms—Infrared (IR) scene projection, mid-infrared (mid-IR) light-emitting diode (LED), type I.

HIGH brightness and high efficiency broadband light sources for the spectral range 2–5 μm are in high demand for industrial chemical sensing, process monitoring and mid-infrared (mid-IR) imaging. A central element of these technologies is an individually addressable emitter array for IR image projection. Several approaches have been used for IR image generation including resistor arrays [1], scanning laser arrays [2], and digital micromirror devices, but light-emitting diode (LED) arrays show promise in this application by offering higher spectral brightness, more compact size, relatively higher efficiency, and the possibility of faster modulation.

This basic research into mid-IR LEDs as an emitter array combines the advantages of high brightness, high dynamic range, uniformity, temperature stability, fast modulation (high frame rate), low cost, and high reliability. Type II interband cascade (IC) LEDs operating in the spectral range 3–5 μm were successfully used for array fabrication [3], but recent progress in the development of Type I GaSb-based mid-IR emitters operating at wavelengths beyond 3 μm will open the way for the application of LED emitter arrays in IR scene projection [4].

The Type I mid-IR GaSb-based LED with a quantum-well active region has demonstrated high output power and internal efficiency [5]. A combination of quinternary AlGaInAsSb barriers and quaternary InGaAsSb quantum wells in the device active area allowed for improvement in hole confinement and reduction of the bandgap difference between barrier and quantum-well materials. This approach reduces quantum defect and heat generation in the active area.

In this letter, we report fundamental research into GaSb-based Type I mid-IR LEDs and LED arrays operating over mid-IR wavelengths up to 3.66 μm. The structures were grown on n-type GaSb substrates using a Veeco GEN950 molecular beam epitaxy system. The active area with four InGaAsSb quantum wells was sandwiched between AlGaAsSb claddings. Two kinds of LED arrays were processed (Fig. 1) to study the effect of current spreading to the array performance. The first was an array with the pixels formed by 100 × 100 μm rectangular windows in the dielectric which separated the metal contact from the epilayer of the structure [Fig. 1(a)]. No grooves were etched between the pixels. Despite the fact that we used a common metallization for all the array pixels, this design can be easily applied to the addressable arrays by depositing a separate contact for each pixel. The second was an array with the 100 × 100 μm rectangular mesa forming 200-μm-wide grooves [Fig. 1(b)]. The epilayer in the grooves was etched down to the buffer layer. After etching, the structure was covered with...
silicon nitride. The windows for the contacts were opened on top of the mesas and on the groove bottom. Both n- and p-type contacts were placed at the epilayer side of the device. Contact deposition of Au:Ti was followed by a layer liftoff process. The wafer was thinned down to 150 μm and cleaved. To enable testing, the 6 × 6 LED array was flip-chip bonded on silicon fan-out chips (Fig. 2).

Mid-IR pictures of some of the working LEDs are shown in Fig. 1 (right side). The contrast between the pixels and the background is much better with the case of deep etched mesas. In the array with no etched grooves, the current spreading leads to emission from the area between the pixels. The effect of current spreading in a diode structure is qualitatively described within a simplified model that includes an infinite plane metal contact at the substrate side and a half-plane metal contact at the epilayer side. Current is injected into the half-plane epilayer contact, while the upper clad works as a current spreading layer. Under the metal contact, the current density is \( J_0 \) and the current flows normally to the p-n junction plane. Away from the contact edge, the normal current density decreases and an in-plane current component appears in the structure. The current density as a function of lateral distance to the contact edge \( x \) is given by [6]

\[
J(x) = \frac{2J_0}{(x/L_c + \sqrt{2})^2}, \quad (x > 0)
\]  

(1)

where

\[
L_c = \sqrt{\frac{dn_e kT}{\rho J_0 e}},
\]

(2)

Here \( d \) is the thickness of the upper clad, \( \rho \) is the resistivity of the upper clad, and \( n_e \) is the diode ideality factor. The voltage drop across the p-n junction increases current spreading and works similarly to current-blocking layers in LED design [7]. The current spreading length \( L_c \) depends on the current density \( J_0 \). The estimations made for the presented LEDs give \( L_c \) ranging from \( \sim 15 \mu m \) (\( J_0 = 1000 \text{ A/cm}^2 \)) to 150 μm (\( J_0 = 10 \text{ A/cm}^2 \)). At low current densities, the current spreading length is of the order of distance between the pixels which leads to the reduction of the contrast between working pixels and the background. This effect is eliminated by etching grooves between the pixels (Fig. 1).

The emission spectra were measured with a Fourier transform infrared (IR) spectrometer and InSb photodetector. The emission spectrum of the device is presented in Fig. 3. Increasing the In content in the quantum-well material and adjusting As content to keep the strain at \( \sim 1.5\% \) made it possible to push the peak operation wavelength to 3.66 μm. As the temperature changed from 300 °K to 100 °K, the emission quantum energy increased at the rate of 0.25 meV/°K. The fringe structure (Fig. 3) is due to interference in the device substrate. The additional spectral peak at the high-energy side of the spectrum is probably due to optical transition from the higher electron sub-band.

The output power of the device was measured using an InSb photodiode and a lock-in amplifier. A gold plated integration sphere with a large aperture was used for light collection and homogenizing the radiation. The collection angle was \( \sim 2\pi \). Using an integration sphere with a large input aperture made the measured output power much less sensitive to the optical adjustment accuracy. This allowed direct, reliable, and reproducible measurements of the total output power of the emitter. The entire setup was calibrated using an IC laser operated at 3.4 μm and a Molecron power meter. The total output power of the 3 × 3 array with no etched grooves is shown in Fig. 4.
The output power increased at low temperatures and reached 1.6 mW at 0.6 A (100 °K).

In conclusion, we demonstrated Type I GaSb-based LEDs operated at wavelengths up to 3.66 μm. The devices demonstrated 200 μW of quasi-continuous-wave optical power at room temperature. Additionally, an individually addressable 6 x 6 array was fabricated. In ongoing work, the device has the potential for increasing brightness and output power through the application of a lens array or modification of the device substrate.

REFERENCES