Improvement in Heat Dissipation by Transfer of IV–VI Epilayers From Silicon to Copper

Y. F. Li, P. J. McCann, A. Sow, C. Yao, and P. C. Kamat

***Abstract*—A successful metallization (Au–InSn alloy) bonding and substrate removal procedure is described for improving epilayer heat dissipation. Two IV–VI semiconductor multiple quantum well (MQW) structures grown on silicon host substrates by molecular beam epitaxy with a CaF_2 (or CaF_2–BaF_2) buffer layer were bonded epilayer down to the tips of a copper bar assembly and then the Si substrates were removed by dissolving the CaF_2 (or CaF_2–BaF_2) buffer layer in water. The bonded IV–VI epilayers were cleaved by separation of the copper bars. Photoluminescence (PL) data before and after transfer showed that an increase in diode laser pumping caused a smaller blue shift in the PL energies for the structures bonded to copper when compared to the as-grown samples. Calculations revealed that epilayers transferred to copper were at least 20 °C cooler than the same epilayers on silicon when illuminated with a continuous wave ($\lambda = 911$ nm) laser at a power density of about 25 W/cm^2.**

***Index Terms*—Epitaxial layer liftoff, heat dissipation, IV–VI semiconductors, metallurgical bonding, photoluminescence (PL), scanning electron microscopy.**

IT IS WELL known that local temperatures in semiconductor active regions are much higher than that of the heat sink during light-emitting diode (LED) or laser diode (LD) operation. This is especially true when the substrate or materials in the laser structure have low thermal conductivity. Excessive active region heating can impede the improvement of semiconductor device operation temperature, limit output powers, and cause rapid device degradation. This problem is particularly severe with IV–VI lead–salt semiconductor materials, which are used for mid-infrared (IR) LD fabrication, since they have extremely low thermal conductivities (for example, PbSe: $\kappa = 0.042$ W/cm K at 300 K) [1], [2]. Up to now, the highest continuous-wave (CW) operation temperature for a IV–VI LD is 223 K [3], while the highest pulsed mode operation temperature is 333 K [4]. The large difference between these two values indicates the large self-heating effect that occurs in these devices.

Recently, above room temperature photoluminescence (PL) from PbSe–PbSrSe multiple quantum well (MQW) materials grown on Si substrates using CaF_2–BaF_2 buffer layers has been demonstrated [5]. Since CaF_2 and BaF_2 materials are water soluble, an effective method for enabling LD device fabrication can involve removal of the Si growth substrate by dissolving the fluoride buffer layer. Active region heat dissipation and LD performance can, thus, be enhanced because the IV–VI epilayer structure can be mounted on a high thermal conductivity material like copper ($\kappa = 3.98$ W/cm K at 300 K). It has been predicted [6] that a greater than 60 °C increase in operating temperature can be achieved by replacing PbSe with Copper. Rappl *et al.* [7] demonstrated such an epitaxial layer transfer procedure which involved one epilayer transfer step and a segmentation method that produced epilayer structures with typical dimensions for edge-emitting diode lasers. To date, however, no improvement in the performance (i.e., better active region heat dissipation) of the IV–VI epilayer structure has been experimentally demonstrated.

In this letter, we describe a new and simple bonding method using thermally deposited indium–tin (InSn) eutectic. Scanning electron microscope (SEM) images of segmented structures show good bonding between the IV–VI epitaxial layer and copper with high reproducibility and smooth cleaved facets along (110) planes of the transferred IV–VI semiconductor epilayers. In addition, PL data clearly show a smaller blue shift for structures bonded to copper as compared to the blue shift for structures on Si as the pumping laser power increases. Calculation reveals that layers transferred to copper remain at least 20 °C cooler than the same epilayers on silicon when illuminated with a CW ($\lambda = 911$ nm) laser at a power density of 28.7 W/cm^2.

The two IV–VI MQW structures used in this study (W331 and W336) were grown by molecular beam epitaxy (MBE) on Si(111) substrates. For W331, the layer structure consisted of a 123-nm CaF_2 layer, an undoped 3-μm $Pb_{0.97}Sr_{0.03}Se$ buffer layer, a 20-period MQW structure with 10-nm wells (PbSe) and 50-nm barriers ($Pb_{0.97}Sr_{0.03}Se$), and a 10-nm PbSe capping layer to protect strontium against oxidation. The other MQW sample (W336) is similar to W331 except that it had a 24-nm CaF_2 layer and a 500-nm BaF_2 buffer layer and a 40-period MQW structure with 20-nm wells (PbSe) and 40-nm barriers ($Pb_{0.97}Sr_{0.03}Se$). Detailed procedures for CaF_2–BaF_2 and IV–VI semiconductor MQW growth on Si(111) substrates are described elsewhere [8]. After growth, sections of the 3-in diameter wafers were cleaved along Si$\{111\}$ planes to produce triangular chips with an approximate area of 20 mm^2.

The bonding metallization structure (see Fig. 1) consisted of thermally deposited Au (120 nm) and InSn eutectic (2 μm) on both the MBE-grown sample and the assembly of a 19×9 array of 500×1080 μm rectangular copper bars held together in a specially designed vise. Bonding was accomplished by placing the MBE sample metallized side down onto the metallized copper bar assembly and heating to 200 °C. Care was taken to align one of the cleaved silicon (111) edges to be

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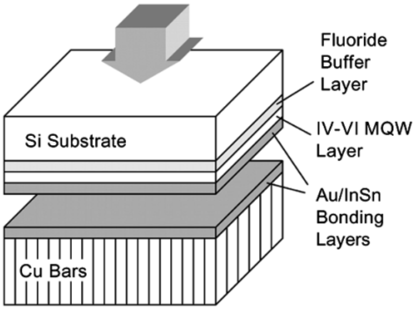

Fig. 1. Bonding arrangement for IV–VI MQW structure on copper bar assembly. Each copper bar is about 500 × 1040 μm × 4 mm and polished before metallization.

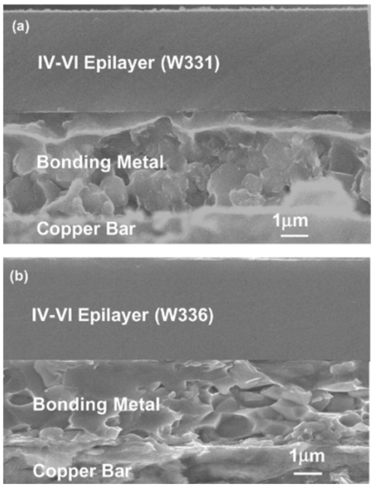

Fig. 2. Cross-sectional scanning electron micrographs showing IV–VI epilayer structures bonded onto copper bars after Si substrate removal and copper bar separation: (a) W331, (b) W336. Smooth (110) cleaved facets in the epilayer are clearly observed for both samples.

parallel with the copper bar edges. During a 30-min heating period, uniform pressure of about 500 g was applied to the backside of the Si substrate. After heating, the copper bar assembly with the bonded IV–VI epilayer was immersed into magnetically stirred deionized water at room temperature in order to remove the Si substrate. Although two different kinds of fluoride buffer layers, CaF_2 and CaF_2–BaF_2, were used there was no significant difference in substrate release time. In each case Si substrate removal took about one day. Scanning electron microscopy was performed with a JEOL JSM-880, and PL was performed using a Fourier transform infrared (FTIR) spectrometer as described previously [5].

Fig. 2 shows cross-sectional SEM micrographs of the IV–VI semiconductor MQW epilayer samples (W331 and W336) bonded to copper using the Au–InSn metallurgy described above. The bonding medium is uniform over hundreds of microns of cleaved sample surface with a thickness of about 4.0 μm, which is consistent with the 4.2-μm total thickness of the deposited metals. The SEM images also show a smooth interface between the IV–VI layer and the bonding metal, indicating that the bonding did not damage the epilayer. At the same time, smooth (110) cleaved facets were also observed.

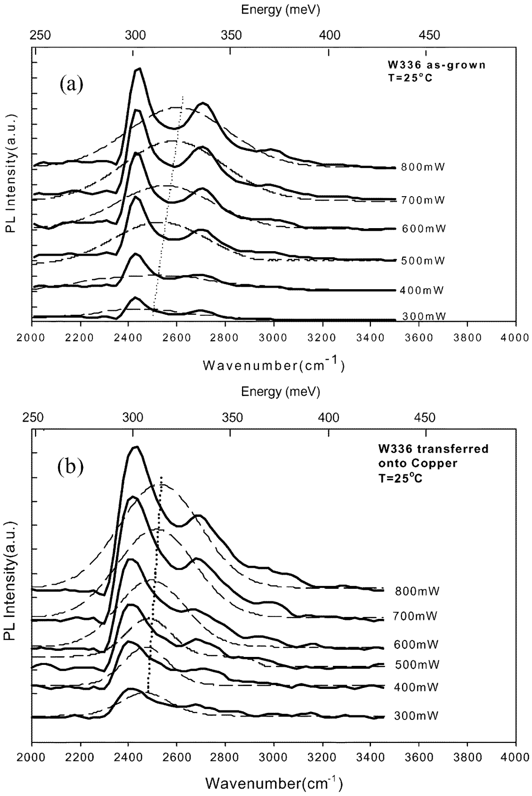

Fig. 3. PL spectra from an as-grown and transferred PbSe–PbSrSe MQW structure for a constant heat sink temperature of 25 °C and different diode laser pump currents. Gaussian fits are also shown. (a) W336 on Si growth substrate, (b) W336 transferred to copper. Solid line: Measured PL spectra. Dashed line: Gaussian fits.

Obtaining (110) cleavage is important because it allows fabrication of in-plane cleaved Fabry–Pérot resonant cavities using (111)-oriented IV–VI MQW materials.

PL measurements from as-grown samples and cleaved IV–VI MQW structures bonded onto the tips of the copper bars were performed using a fiber-coupled diode laser with a peak emission wavelength of 911 nm. The diode laser illuminated the samples from a 45° angle and produced a spot size of about 2 mm in diameter. The luminescence from sample surface was collected by a 2-in-diameter gold-coated off-axis parabolic mirror and passed through a modular FTIR spectrometer (Oriel, MIR8000). The experimental setup was the same as described in [5] except that a liquid nitrogen cooled photoconductive HgCdTe detector with a 13-μm cutoff was used. The diode laser injection current was varied from 0.5 to 1.8 A, which approximately corresponded to a linear variation in pump power (density) from 200 (6.3 W/cm^2) to 880 mW (28.7 W/cm^2). The temperature of the copper bar was stabilized with a single-stage thermoelectric cooler (TEC) module and measured with a resistance temperature detector sensor placed near the sample on a copper plate submount attached to the TEC module. Fig. 3 shows mid-IR surface emission spectra of an as-grown and transferred IV–VI MQW sample (W336) for a range of diode laser pumping powers at a constant heat sink temperature of 25 °C. Gaussian fits to the measured spectra, which are dominated by Fabry–Pérot interference fringes caused by resonance in the optical cavity formed by the layer, are also shown in

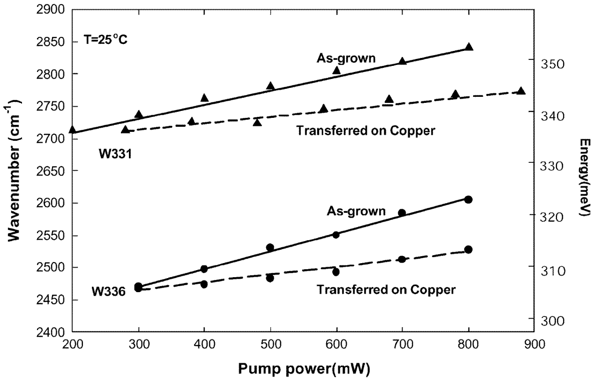

Fig. 4. Comparison of PL energy peak shifts due to increasing diode laser pumping power. (—▲—) As-grown W331. (—•—) As-grown W336. (- -▲- -) Transferred W331. (- -•-- -) Transferred W336.

Fig. 3. It is clearly observed that bonding, substrate removal, and cleaving did not degrade the light-emitting properties of this MQW structure.

With increasing diode laser pumping power, blue shifts in the PL peak energies are observed with both as-grown and transferred samples (see Fig. 4). PL peak energy increase is due to localized heating of the IV–VI material (a significant amount of electron–phonon scattering is expected due to the large 1.36-eV photon energy relative to the 0.47-eV bandgap of the PbSrSe barrier layers) and the associated increase in the bandgap energy [9] caused by higher photon flux from the near-IR laser [10]. Table I lists measured interband transition energies for different optical pumping levels (and heating) along with calculated IV–VI epilayer temperatures (using the 0.41-meV/K temperature-tuning coefficient for PbSe) for two different MQW samples on silicon and copper. Epilayer structures bonded to copper exhibit a smaller blue shift at higher pumping levels and, thus, less heating. Results show that epilayers bonded to copper are more than 20 °C cooler than the same epilayers on silicon when exposed to a CW ($\lambda = 911$ nm) laser at a pump power (density) of 800 mW (25 W/cm^2).

It should be pointed out that the 20 °C improvement demonstrated here was with comparison to samples on silicon, which has fairly good thermal conductivity. If compared to layers on a BaF$_2$ or a IV–VI substrate, the improvement would be much larger. The successful transfer of MBE-grown MQW structures from growth substrates to higher thermal conductivity copper without degradation of the optical emission properties shows that it should be possible to fabricate mid-IR lasers with CW emission at room temperature.

In summary, transfer of MBE-grown IV–VI semiconductor epilayer structures onto copper bars using a new bonding, substrate removal, and cleaving method was successfully demonstrated. SEM images of segmented structures showed good bonding between the IV–VI epilayers and copper with high reproducibility. In addition, smooth cleaved (110) facets could also be obtained, which makes it possible to fabricate edge-emitting mid-IR lasers from (111)-oriented IV–VI MQW materials. PL measurements showed that epilayers exposed to a ~25-W/cm^2 optical flux ($\lambda = 911$ nm) were about 20 °C cooler than the same epilayer on the silicon growth substrate.

TABLE I

MEASURED INTERBAND TRANSITION ENERGIES BETWEEN NORMAL L-VALLEY STATES AS DETERMINED BY DIFFERENTIAL TRANSMISSION SPECTROSCOPY (DTS), WHERE THERE IS NONSIGNIFICANT EPILAYER HEATING [11], AND PL, WHERE THERE IS SIGNIFICANT EPILAYER HEATING. LOCALIZED EPILAYER TEMPERATURES AT HIGH PL PUMPING POWERS ARE ALSO LISTED. NOTE THE MUCH LOWER TEMPERATURES FOR THE EPILAYERS-ON-COPPER SAMPLES

Sample	**Substrate**	**DTS $(1\text{-}1)^N$**	**PL Peak Energy T_H =25°C (meV)**		**Blue Shift**	**Epilayer Temperature**
		meV	**300 mW**	**800 mW**	**meV**	**at 800 mW (°C)**
W331 (L_{QW}=10 nm)	Si	329	336.2	352.1	15.9	83.5
	Cu	329	335.6	343.2	7.6	61.6
W336 (L_{QW}=20 nm)	Si	296	306.3	323	16.7	93.3
	Cu	296	305.9	313.3	7.4	68.9

These results show the role of higher substrate thermal conductivity in enhancing heat dissipation from optically active materials. Future work should focus on demonstrating mid-IR laser emission from packaged devices.

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