FULL REFERENCE: PHOTONICS TECHNOLOGY LETTERS, VOL. 23, NO. 1, JANUARY 1, 2011
Digital Object Identifier (DOI) 10.1109/LPT.2010.2090517

Enhancement in Light Emission from Hg-Cd-Te due to Surface Patterning

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***Abstract*—Enhancement of light emission from HgCdTe due to surface patterning has been studied by means of photoluminescence (PL) spectroscopy. A triangular pattern of circular holes was etched into the CdTe layer grown on top of HgCdTe thin-film and multiple quantum well samples. Two different pattern lattice constants a_G were used, giving lattice constant to emission wavelength ratio of 0.9, 1.2, and 2.1. The surface pattern was found to give 26-35% enhancement in measured PL intensity.**

***Index Terms*—2D grating, HgCdTe, integrated optics, photoluminescence**

I. Introduction

THE semiconductor $Hg_{1-x}Cd_xTe$ has a direct band gap which can be tuned, through the Cd mole fraction *x*, from 0 eV in the semi-metal HgTe to 1.6 eV in CdTe at 77 K. The material therefore covers the entire infrared (IR) range, and the overall highest performance mid-wavelength and long-wavelength infrared (MWIR and LWIR) detectors are made with HgCdTe [1]. It is, however, a difficult material to grow, and there has been a continuous effort to improve the crystal quality, and thereby the quantum efficiency, of HgCdTe. Detector elements fabricated on high quality layers with anti-reflective (AR) coating can have a total quantum efficiency close to 100%.

There is also a growing interest in devices that emit light in the MWIR range, for applications as different as gas detection and free-space communication. Both HgCdTe light emitting diodes (LEDs) [2]-[4], optically pumped lasers [5], [6], and diode lasers [7], [8] have been demonstrated. A problem for light emitting devices in narrow gap semiconductors is non-radiative loss mechanisms. For MWIR HgCdTe, Auger recombination is the dominant process and limiting factor, and most devices must be run at low temperatures. For LEDs, internal quantum efficiencies η_{int} as high as 17% at 77 K and 6% at 300 K have been demonstrated [2]. However, HgCdTe focus has been on IR detectors, and light emitting devices have not been extensively developed yet.

Coupling light from air into HgCdTe is facilitated by the higher index of refraction *n* in the semiconductor than in air and by the detector scene being far away so that the light is incident approximately normal to the surface. Coupling light out of HgCdTe is a very different matter, encountering the same problem as light-emitting devices in many other semiconductor materials: The relatively large *n* (typically 3.5) gives a small critical angle of total internal reflection (TIR), and only ~ 2% of the generated radiation is transmitted out of the semiconductor [9]. Therefore, even though η_{int} of HgCdTe light emitting devices may be reasonable, the light output will be very small.

Methods that can improve η_{ext} are therefore of great interest. Many LEDs are encapsulated in a dielectric dome that improves emission (emitted radiation propagates almost ⊥ to the surface), although the available indices of refraction are too low for the scheme to work really well [10]. Another method to enhance η_{ext} is to increase the surface roughness, either in a random or orderly fashion. Randomly roughened LED surfaces combined with a reflective back offer the photons multiple chances of escaping. Radiation emitted

Manuscript received August 27, 2010.
The work was funded by Norwegian MOD and support for characterizarion given by the AFOSR under grant number FA9550-06-1-0484, P00002..
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outside the escape cone is scattered back into the crystal by the rough surface and then reflected from the back of the LED. This angular randomisation continues until the photon either falls within the TIR cone or is absorbed by the crystal, and Schnitzer *et al*. [11] and Fujii *et al*. [12] have thus increased their LED η_{ext} by 233% (AlGaAs/GaAs) and 130% (GaN). Silicon is a very inefficient emitter, and for Si much higher enhancement factors have been observed [9].

Regularly patterned surfaces can increase the emission by scattering the light from outside to inside the escape cone through Bragg diffraction. For a triangular lattice of circular holes with a reflective backside contact layer, Ichikawa and Baba [13] reported a 70-170% increase in η_{ext} for near-infrared GaInAsP LEDs. Kim *et al*. [14] and Byeon *et al*. [15] also used a triangular pattern of holes, but without a reflective backside layer, and reported increases in η_{ext} of 30-120% for red AlGaAs LEDs and 23% for blue InGaN LEDs, respectively. Such a periodic pattern of air-filled holes may be considered to be a two-dimensional (2D) photonic crystal layer, but it is mainly a 2D diffraction grating. To escape from the semiconductor, light waves must have a small (or zero) component of the wave vector $\boldsymbol{k}$ along the surface. The 2D grating prevents light trapping by changing the tangential component by a grating reciprocal lattice vector [13], [16].

II. Experimental procedures

All samples were grown by molecular beam epitaxy (MBE) on (211)B CdZnTe substrates. Results on two samples from the same thin film layer (TF-A and TF-B) and two samples from the same multiple quantum well (MQW) layer (MQW-A and MQW-B) are presented here. As HgCdTe surfaces are easily damaged by etching, the holes were etched in a 0.4 - 0.5 µm CdTe layer that was grown *in-situ* on top of all the samples. CdTe provides an excellent passivation layer for HgCdTe, with its large band gap of 1.6 eV and a very small lattice mismatch of < 0.3%. Photolithography and a Br_2:HBr spray etch was used, and the holes extended almost down to the CdTe/HgCdTe interface.

We scaled the triangular pattern of the red LEDs of Kim *et al.* [14] to the MWIR region. For our samples with grating lattice constant a_G = 4.5 and 6.0 µm and emission wavelength in air λ_{air} = 5 or 2.8 µm, the ratio $r_{a\text{-}\lambda} = a_G/\lambda_{air}$ was 0.9, 1.2, and 2.1, which is in the same range as in [14]. We also kept the mask hole diameter to lattice parameter ratio fixed at d_G/a_G = 0.5; however, the actual diameter of the etched holes turned out to be somewhat larger in our samples. According to [13], $r_{a\text{-}\lambda}$ values of 0.9 – 2.1 leave us well within the range where the outgoing waves are strongly diffracted by the surface pattern.

The hole pattern covered only part of the sample surface, so that both patterned and non-patterned parts of the sample could be measured in the same PL experiment. To avoid influencing the incoming laser intensity by the surface pattern, the samples were illuminated from the substrate (back) side through a slit (6.5 mm × 2.5 mm) in the sample holder and coldfinger, as shown in Fig. 1(a). The sample was glued to the sample holder so that approx. half the length of the slit was covered by patterned area, the other half by non-patterned area. The wavelength and beam diameter of the excitation laser were λ_{laser} = 2.01 µm and d_{laser} ~ 1 mm. During the measurements the laser and optics remained stationary, while the cryostat was moved along the length of the slit between subsequent spectra. The collection mirror covered an angle ± 18.6 º around the surface normal. The spectra were recorded by a Bruker IFS 66 Fourier transform infrared (FTIR) spectrometer.

The experimental setup put certain limitations on the sample design. The MQW samples had four QWs followed by a laser absorption layer and the CdTe passivation layer, as shown in Fig. 1(b). The QW effective bandgap had to be well above the detector cutoff of 210 meV. The band gap of the barrier layers had to be large enough to create quantum wells for the photoexcited carriers, but small enough that the laser could be absorbed in these layers.

The laser light enters the sample from the substrate side and is partly absorbed in/partly transmitted through the MQWs and the absorption layer. At the HgCdTe/CdTe interface some of the laser light will be reflected back into the sample, but the amount of reflected light can be influenced by the grating. The absorption layer was designed to absorb enough laser light to prevent photons making multiple passes through the MQWs, while at the same time transmitting the QW PL light.

Taking all this into consideration, we designed the MQWs to have 6.6 nm wide x = 0.35 well layers surrounded by 30 nm wide x = 0.50 barrier layers and a 1 µm thick x = 0.44 laser absorption layer. Using an absorption coefficient of 1.1 x 10^4 cm^{-1} [17], and approximate indices of refraction 3.0 and 3.4 for the CdTe and absorption layers [18], we find that < 5% of the laser light will reach the MQWs a second time. For the thin-film samples, we wanted to explore smaller $r_{a\text{-}\lambda}$. Also, the film had to be thick enough for the laser light to be absorbed before reaching the CdTe layers. This resulted in a $Hg_{0.71}Cd_{0.29}Te$ film of thickness 4 µm.

Ideally, the CdTe layer should also have satisfied the requirements of an AR coating. However, given the materials in the samples and the mask geometry, it was not possible to design an optimal AR coating from the grating layer. Such a coating should have $n_{AR} = (n_{HgCdTe} * n_{air})^{½}$ and thickness $d_{AR} = \lambda_{AR}/4$, where λ_{AR} is the wavelength of the PL light in the AR coating, which in our samples means n_{AR} ~ 1.8 and d_{AR} ~ 0.7 or 0.4 µm. Gjessing *et al*. [19] have developed a method for calculating the effective refractive index for SiO_2 columns in Si, in the limit of small a_G (the static electric field approximation). Scaling their results to air columns in CdTe results in an approximate index of refraction in the grating layer of n_G = 2.3, which is too high. No combination of $Hg_{1-x}Cd_xTe$ x-values in the grating layer and the underlying CdHgTe layer allows the expression for n_{AR} to be fulfilled, but using CdTe in the top layer brings us the closest possible for the given value of d_G/a_G.

III. Results and Discussion

Typical spectra originating in patterned and non-patterned sample areas are shown in Fig. 2(a) for TF-A at 120 K and Fig. 2(b) for MQW-B at 11 K. An optical micrograph of the hole pattern is shown in Fig. 2(c). The increase in PL intensity from the patterned areas is 27% for TF-A and 35% for the MQW (lower energy) peak in MQW-B. The shift in peak energy between patterned and non-patterned spectra is due to lateral inhomogeneity in the composition of the layers across the samples. The direction of the shift did not affect the magnitude of the increase in intensity from patterned areas.

The low-energy peak in the MQW-B spectra originates in MQW transitions, whereas the high-energy peak is due to band-to-band recombination in the laser absorption layer. Only the MQW peak was included in the integrated PL intensity from the MQW samples, as the intensity of the absorption layer PL peak is influenced by the amount of reflected laser light from the HgCdTe/CdTe interface.

Fig. 2(d) shows the integrated PL peak intensity as a function of position in the slit for the four samples; TF-A, TF-B, MQW-A, and MQW-B. The gradual increase from non-patterned to patterned areas is mainly due to the size of the laser spot (1 mm). The increase in PL intensity from the patterned area relative to non-patterned area was 30, 35, 27, and 26% for MQW-A ($r_{a\text{-}\lambda}$ = 2.1), MQW-B ($r_{a\text{-}\lambda}$ = 2.1), TF- A ($r_{a\text{-}\lambda}$ = 0.9), and TF- B ($r_{a\text{-}\lambda}$ = 1.2), respectively.

We can compare our results with those in [14] and [15] (triangular hole pattern, without reflective backside layer). In [14] the enhancement in η_{ext} was between 30% and 120%, with values exceeding 75% for $0.6 < r_{a\text{-}\lambda} < 2$. Our samples had a smaller enhancement, ~ 30%, for $r_{a\text{-}\lambda}$ = 0.9, 1.2 and 2.1. A larger range for $r_{a\text{-}\lambda}$ in our samples should probably be explored. We obtained a somewhat larger enhancement for $r_{a\text{-}\lambda}$ = 2.1 (30-35%) than for $r_{a\text{-}\lambda}$ = 0.9 or 1.2 (26-27%). It is not clear whether this was due to $r_{a\text{-}\lambda}$ or some sample-dependent feature. Our enhancement is larger than the 23% enhancement in EL for $r_{a\text{-}\lambda}$ = 1.5 reported in [15]. Other possible limiting factors for the emission enhancement in our samples may be non-optimal grating layer fill-factor, non-optimal AR coating, areas with poorer pattern, or non-optimal shape of the holes.

This is the first report of light emission enhancement due to surface patterning in HgCdTe. Further work should include photolithography or electron beam lithography with a larger pattern fill-factor, which will decrease n_G, thus resulting in a better AR coating. To obtain larger improvement, a HgTe reflective layer could be grown between the substrate and the HgCdTe layers. Finally, complete LEDs with a 2D grating surface pattern should be fabricated.

References

[1] M. A. Kinch, “HgCdTe: Recent Trends in the Ultimate IR Semiconductor,” *J. Electron. Mater.*, vol. 39, pp. 1043-1052, Jul. 2010.

[2] P. Bouchut *et al*., “High efficiency infrared light-emitting-diodes made in liquid phase epitaxy and molecular beam epitaxy HgCdTe layers,“ *J. Vac. Sci. Technol. B*, vol. 9, pp. 1794-1978, May 1991.

[3] J. L. Pautrat, E. Hadji, J. Bleuse, and N. Magnea, “Resonant-cavity infrared optoelectronic devices ,” *J. Electron. Mater.*, vol. 26, pp. 667-672, Jun. 1997.

[4] R. Haakenaasen *et al*., “HgCdTe quantum-well light-emitting diodes”, in preparation.

[5] I. Melngailis and A. J. Strauss, “Spontaneous and coherent photoluminescence in $Cd_xHg_{1-x}Te$ - (Laser material 3-15mu 12 and 77 degrees K laser excitation E),“ *Appl. Phys. Lett.*, vol. 8, pp. 179, 1966.

[6] C. Roux, E. Hadji, and J.-L. Pautrat, “2.6 µm optically pumped vertical-cavity surface-emitting laser in the CdHgTe system,” *Appl. Phys. Lett.*, vol. 75, pp. 3763-3765, Sep. 1999.

[7] M. Zandian, J. M. Arias, R. Zucca, R. V. Gil, and S. H. Shin, “HgCdTe double heterostructure injection laser grown by molecular beam epitaxy,” *Appl. Phys. Lett.*, vol. 59, pp. 1022-1024, Aug. 1991.

[8] A. Million *et al*., “HgCdTe double-heterostructure for infrared injection-laser,” *J. Cryst. Growth*, vol. 127, pp. 291-295, Feb. 1993.

[9] M. Zelsmann *et al*., “Seventy-fold enhancement of light extraction from a defectless photonic crystal made on silicon-on-insulator” *Appl. Phys. Lett.* vol. 83, pp. 2542-2544, Sep. 2003.

[10] W. N. Carr and G. E. Pittman, “One-watt GaAs p-n junction infrared source,“ *Appl. Phys. Lett.*, vol. 3, pp. 173-175, 1963.

[11] I. Schnitzer, E. Yablonovitch, C. Caneau, T. J. Gmitter, and A. Scherer, “30-percent external quantum efficiency from surface textured, thin-film light-emitting diodes,“ *Appl. Phys. Lett.*, vol. 63, pp. 2174-2176, Oct. 1993.

[12] T. Fujii *et al.*, “Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening,“ *Appl. Phys. Lett.*, vol. 84, pp. 855-857, Feb. 2004.

[13] H. Ichikawa and T. Baba, “Efficiency enhancement in a light-emitting diode with a two-dimensional surface grating photonic crystal,“ *Appl. Phys. Lett.*, vol. 84, pp. 457-459, Jan. 2004.

[14] T. Kim *et al.*, “Photonic crystal structure effect on the enhancement in the external quantum efficiency of a red LED,“ *IEEE Phot. Technol. Lett.*, vol. 18, pp. 1876-1878, Sep. 2006.

[15] K.-J. Byeon *et al.*, “Enhancement of the photon extraction of green and blue LEDs by patterning the indium tin oxide top layer,“ *Semicond. Sci. Technol.*, vol. 24, 105004-1, Oct. 2009.

[16] M. Boroditsky *et al*., “Spontaneous emission extraction and Purcell enhancement from thin-film 2-D photonic crystals,“ *J. Lightwave Technol.*, vol. 17, pp. 2096-2112, Nov. 1999.

[17] B. Li, J. H. Chu, Y. Chang, Y. S. Gui, D. Y. Tang, “Optical absorption above the energy band gap in $Hg_{1-x}Cd_xTe$,” *Infrared Phys. Technol.*, vol. 37, pp. 525-531, Jun. 1996.

[18] P. M. Amirtharaj, “Mercury Cadmium Telluride ($Hg_{1-x}Cd_xTe$),” in *Handbook of optical constants of solids II*, E. D. Palik, Ed. San Diego: Academic Press, 1998), pp. 655-690.

[19] J. Gjessing, E. S. Marstein, and A. Sudbø, ”2D back-side diffraction grating for improved light trapping in thin silicon solar cells,” *Optics Express*, vol. 18, pp. 5481-5495, Mar. 2010.

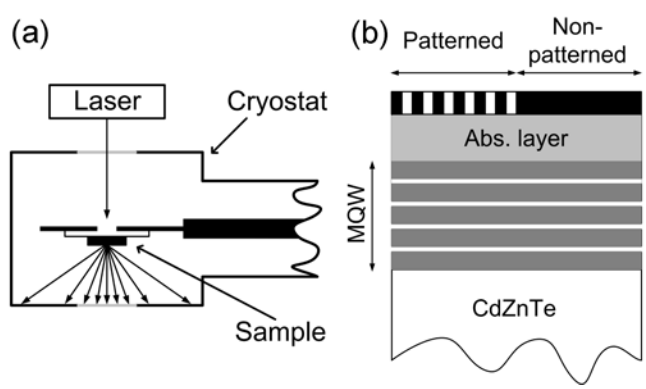

Fig. 1. Schematic drawings of (a) the cryostat, in the plane of the laser beam propagation, and (b) the MQW samples, which consist of a four-period 6.6 nm x = 0.35/ 30 nm x = 0.50 MQW structure followed by a 1 µm x = 0.44 laser absorption layer.

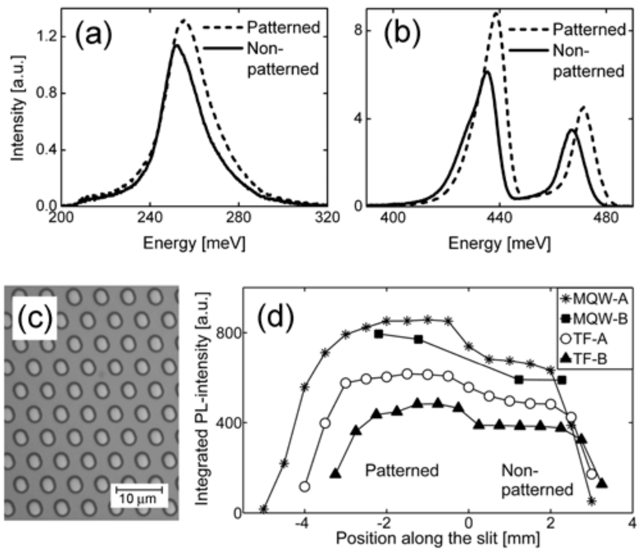

Fig. 2. PL-spectra from patterned (dotted line) and non-patterned (solid line) areas of (a) TF-A at 120 K and (b) MQW-B at 11 K. (c) Optical micrograph showing part of the surface pattern of TF-B. (d) Integrated PL peak intensity vs. position for the four samples, with 0 mm corresponding to the boundary between patterned and non-patterned surface. The curves are vertically displaced for clarity.