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# Fabrication of Short GaAs Wet-Etched Mirror Lasers and Their Complex Spectral Behavior

Fouad Karouta, *Member, IEEE*, E. Smalbrugge, W. C. van der Vleuten, S. Gaillard, and Gerard A. Acket

**Abstract**—A versatile fabrication technique for GaAs–AlGaAs wet-etched mirror lasers is presented. This technique works independently of the Al concentration in the cladding layers up to a value of 70%, and it requires four photolithography steps. Ridge waveguide lasers have been successfully processed using a double heterostructure (DHS) as well as graded index separate confinement heterostructures (GRINSCH) having different quantum-well (QW) active layers. This technique is used to fabricate short-cavity lasers in GRINSCH structures having GaAs multiple-quantum-well (MQW) or bulk active layers. Laser operation was obtained in a 29- $\mu\text{m}$ -long device using a 5-QW structure. Short lasers with QW active layers show a complex spectral behavior. These lasers operate at higher current densities ( $\sim 20 \text{ kA/cm}^2$ ) and emit light at more than one wavelength. This implies that higher order transitions are involved which is not the case when using a bulk GaAs active layer. Besides the two peaks corresponding to the  $n = 1$  and  $n = 2$  transitions, we found an intermediate peak which corresponds presumably to the forbidden transition E1–HH2.

**Index Terms**—Etched mirror lasers, GaAs, quantized states, quantum-well devices, semiconductor lasers, wet etching.

## I. INTRODUCTION

ETCHED mirror lasers have a potential use in monolithic integration in optoelectronic integrated circuits (OEIC). Many authors have reported about etched mirror lasers using dry etching techniques. Only a few papers [1]–[5] describe similar work using wet chemical etch techniques aligning the mirrors along the  $[011]$  direction. In these papers the technique described was used to process only one specific double heterostructure (DHS) laser structure having a bulk GaAs active layer. Laser operation in CW mode was reported only by Wada *et al.* [5] using also a bulk GaAs active layer. In this paper we present in Section II a versatile processing technique for wet-etched mirror lasers (WEML's) which has been successfully applied to various laser structures having quantum-well (QW) active layers of GaAs, InGaAs, or AlGaAs. In Section III, we deal with the spectral behavior of short lasers processed using this technique.

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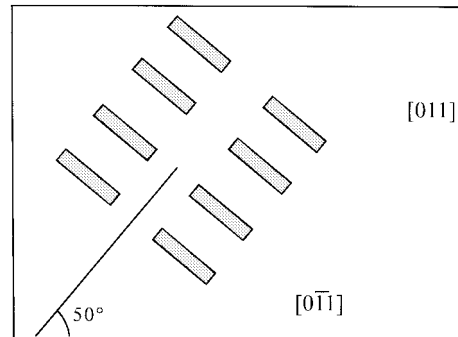


Fig. 1. WEML mirror orientation.

## II. PROCESSING TECHNIQUE AND RESULTS

### A. General Background

Numerous etching solutions based on hydrogen peroxide with ammonia, sulfuric acid, or phosphoric acid were tested under different conditions with the objective of obtaining vertical and smooth side walls. All GaAs substrates are  $(100)$  oriented. Besides the composition and the temperature of these solutions, we varied the orientation of the stripes along the  $[011]$  and  $[0\bar{1}1]$  axes and many intermediate directions. We have found that to ensure vertical and smooth mirrors the mask which defines the mirrors should be placed under an angle of  $50^\circ$  to the  $[0\bar{1}1]$  direction, as shown in Fig. 1.

This orientation is not commonly used in laser technology. A possible explanation of these results can be as follows: when a diffusion-limited etch solution is used to etch stripes parallel to the  $[011]$  direction, it results in negative slope walls (dove tail shape). By allowing longer etch time there will be a tendency to obtain positive slope walls. Similar results regarding the dependence of the shape of the etched groove on the etch time are reported in the literature [2], [4]. Theoretically vertical side walls are obtainable with any etch solution when aligning at  $45^\circ$  between the  $[011]$  and the  $[0\bar{1}1]$  directions. In practice some experimental research is required before reaching such a result. In our case the orientation of  $50^\circ$  toward the  $[0\bar{1}1]$  direction means that the stripe is closer ( $40^\circ$  only) to the  $[011]$  direction than to the  $[0\bar{1}1]$  direction. In this case there will be a tendency toward slightly negative slope walls. This is compensated by the tendency of diffusion-limited etch solutions to produce positive slope walls.

In our experimental conditions we found that a vertical and smooth wall is always obtained when the etch is performed following the  $50^\circ$  orientation and when the etch depth is

between 3 and 5.5  $\mu\text{m}$ . An etch depth of less than 3  $\mu\text{m}$  results in negative slope walls while a deeper etch ( $>5.5 \mu\text{m}$ ) leads to positive slope walls. A special point of attention is the underetch when using this orientation, which is very important and almost equal to the etch depth itself.

### B. Description of the Processing Technique

Our versatile technique to fabricate a WEML is applicable to a wide range of GaAs–AlGaAs laser structures including a DHS with GaAs bulk active layer and three different QW graded index separate confinement heterostructures (GRINSCH) structures having different active layers. To our knowledge this is the first report of a WEML exhibiting CW laser performance in GRINSCH single-quantum-well (SQW) laser structures with GaAs or InGaAs as the active layer.

This processing technique has been successfully applied to:

- 1) MOVPE-grown DHS with 30% Al in the confinement layers and 0.15- $\mu\text{m}$  GaAs active layer;
- 2) MBE-grown GRINSCH with a maximum of 70% Al in the confinement layers and as active layers:
  - a) 7-nm SQW GaAs.
  - b) 8-nm strained  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$  SQW;
  - c) six QW's of 6 nm of  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ .

The latter structure exhibits laser operation in the pulse mode only.

The processing technique requires four steps of photolithography instead of one for cleaved lasers (CL's). Each of these steps is accompanied by some processing steps:

- 1) definition of mesa blocks 8 and 16  $\mu\text{m}$  wide followed by:
  - a) etching the ridge waveguides using  $\text{H}_3\text{PO}_4\text{:H}_2\text{O}_2\text{:CH}_3\text{OH}$  (1:1:3) at 0  $^\circ\text{C}$ ;
  - b) deposition of  $\text{SiO}_2$  by remote plasma enhanced chemical vapor deposition (RPECVD) at low temperature (110  $^\circ\text{C}$ );
  - c) annealing step of the  $\text{SiO}_2$  in  $\text{H}_2$  ambient;
- 2) definition of the p-type contact metallization:
  - a) Ti–Pt–Au (50–20–200 nm) is used for this contact;
- 3) definition of openings (stripes) in the  $\text{SiO}_2$  layer:
  - a) etch the openings using a buffered HF solution—the edge of the etched  $\text{SiO}_2$  should be as close as possible to the p-metal edge; in these openings the laser mirrors will be etched;
- 4) definition of stripes for etching the mirrors:
  - a) etching the mirrors in  $\text{H}_3\text{PO}_4\text{:H}_2\text{O}_2\text{:CH}_3\text{OH}$  (1:1:1) at 20  $^\circ\text{C}$ ; the etch rate is 3.6  $\mu\text{m}/\text{min}$ ;
  - b) annealing of the p-metallization in Ar ambient.

Afterwards, the processing is similar to that of a CL, i.e., thinning the substrate by mechanical and chemical polishing down to  $\pm 120 \mu\text{m}$ . A metallization of Ge–Ni–Au (20–15–200 nm) is used as n-type contact on the back side of the sample followed by an annealing step. As the mirrors are not aligned to a cleavage plane, full line scribing was used to separate the samples in bars of five to six lasers. As the etch depth of the mirrors does not exceed 5.5  $\mu\text{m}$  and as the full line scribe

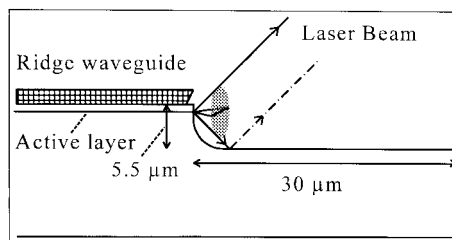


Fig. 2. Schematic cross section of an etched laser.

is placed at equal distance between two mirrors of adjacent lasers (about 30  $\mu\text{m}$ ), the laser light beam is partially reflected by the bottom, as shown in Fig. 2. This affects the shape of the transversal far-field pattern as will be discussed later. A simple mounting on a half DIL package is used to characterize the lasers under pulsed as well as in CW conditions. No heat sink and no mirror coatings were used.

### C. Results and Discussions

1) *DH Structure*: Devices with 16- $\mu\text{m}$ -wide ridge waveguide and 250- $\mu\text{m}$ -long show laser operation with threshold currents ranging from 52 to 70 mA under pulsed conditions ( $J_{\text{th}} = 1.6\text{--}2.1 \text{ kA}/\text{cm}^2$ ) and 120 mA in CW ( $J_{\text{th}} = 3.7 \text{ kA}/\text{cm}^2$ ).

2) *GRINSCH–GaAs SQW*: Devices with various geometries exhibit laser operation in CW mode at room temperature with threshold currents as low as 16 mA ( $J_{\text{th}} = 870 \text{ A}/\text{cm}^2$ ); the lowest  $J_{\text{th}}$  was 440  $\text{A}/\text{cm}^2$  obtained with 650- $\mu\text{m}$ -long lasers.

3) *GRINSCH–In<sub>0.2</sub>Ga<sub>0.8</sub>As SQW*: Lasers 950  $\mu\text{m}$  long and 8 and 16  $\mu\text{m}$  wide were processed. They show CW laser performance with a threshold current of 80 mA ( $J_{\text{th}} = 500 \text{ A}/\text{cm}^2$ ).

4) *GRINSCH–6xAl<sub>0.2</sub>Ga<sub>0.8</sub>As QW's*: As with the strained layer laser structure, mesa blocks 8 and 16  $\mu\text{m}$  wide and 950  $\mu\text{m}$  long are defined and etched. Laser operation was obtained only in a pulsed regime at a wavelength of 730 nm. The lowest threshold current obtained is 190 mA. The large number of QW's (6) which is used in this structure is responsible for this higher threshold current.

All the above-mentioned lasers showed similar  $L$ – $I$  curves and the differential efficiencies of WEML's were comparable to those of cleaved-mirror lasers (Fig. 3). The transversal far-field (FF $\perp$ ) pattern of a GRINSCH–GaAs etched laser is shown in Fig. 4 and compared to that of a cleaved laser of the same structure. The unusual FF $\perp$  pattern can be explained by interference effects due to reflection of the laser light beam on the substrate (as shown in Fig. 2). Fig. 5 shows a SEM photo of an etched mirror.

## III. COMPLEX SPECTRAL BEHAVIOR OF SHORT LASERS WITH GAAS QW'S

### A. General

A set of masks has been designed and realized which allows the fabrication of WEML's in a wide range of cavity lengths going from 11 to 750  $\mu\text{m}$ . The ridge waveguide width is

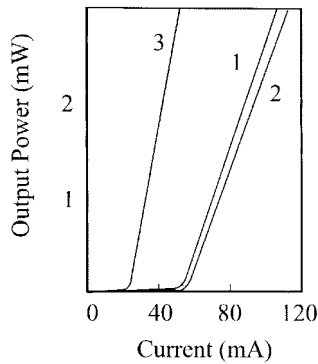


Fig. 3.  $L$ - $I$  characteristics of etched lasers with a ridge width of  $8\ \mu\text{m}$  (1, 2) and a  $4\text{-}\mu\text{m}$ -wide cleaved laser (3) made from the InGaAs SQW laser structure.

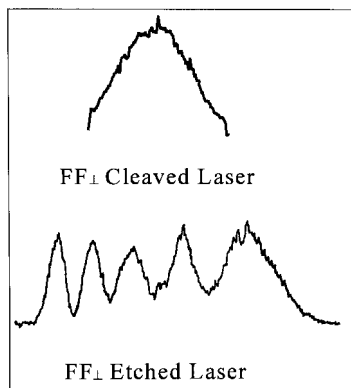


Fig. 4. Far-field patterns of a cleaved laser (top) and an etched laser (bottom).

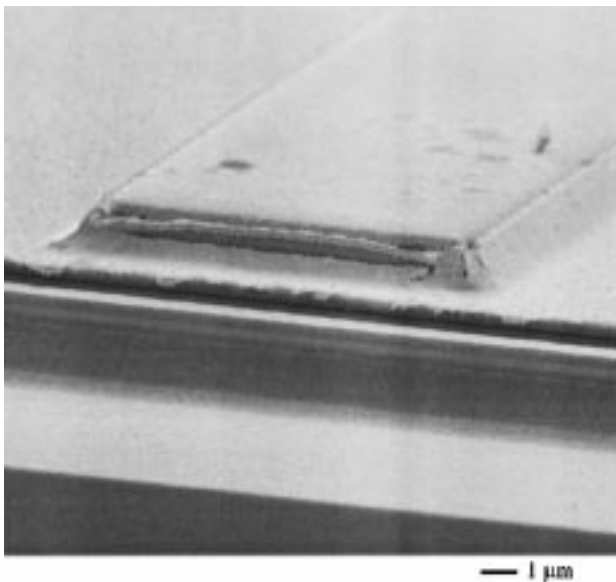


Fig. 5. Frontal SEM photo of an etched mirror.

also varied from  $4$  to  $10\ \mu\text{m}$ . Using these masks, WEML's were processed from four GRINSCH laser structures having, respectively, two, three, and five QW's and a bulk active layer. All QW's were  $7\text{-nm}$ -thick GaAs and the bulk was  $50\text{-nm}$ -thick GaAs. The GRINSCH structures are similar to

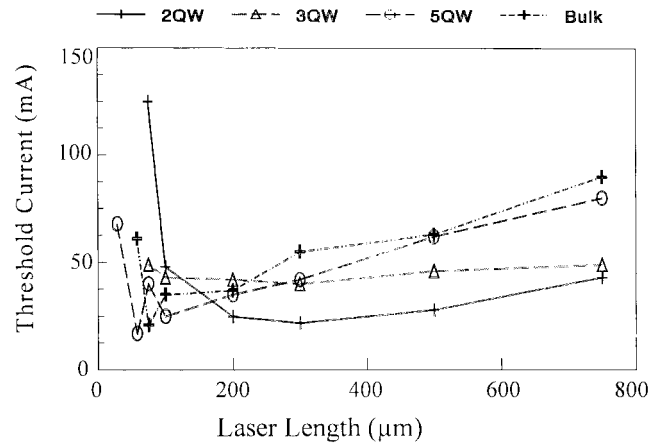


Fig. 6. Threshold current versus laser length for various laser structures.  $W = 10\ \mu\text{m}$ .

those used in Section II. The barriers contained 20% Al and the maximum Al-content in the cladding layers was 70%. The characterization of the devices is carried out under pulse conditions. The shortest laser we obtained was  $29\ \mu\text{m}$  long (GRINSCH—five QW's) having a threshold current of  $70\ \text{mA}$  and exhibiting a maximum output power of  $0.5\ \text{mW}$ .

### B. Threshold Current versus Cavity Length

It is well known that the threshold current ( $I_{\text{th}}$ ) of lasers, for a given structure, decreases almost linearly when shortening the cavity length until a certain critical value which depends essentially of the laser structure itself. Then shorter lasers require higher currents to reach the lasing threshold as the gain of the cavity becomes insufficient. A previous work [6] in cleaved lasers showed a similar behavior in identical GRINSCH structures with one or two QW's. WEML's offer the advantage of varying the cavity length down to very small values as no technological restriction in terms of cleavage is involved. Due to a poor yield in the short lasers, some values are not expected to be representative. Fig. 6 shows the threshold current versus cavity length for all laser structures. This figure reveals that threshold current keeps decreasing with shorter cavity lengths until a certain limit below which the current increases dramatically. The more QW's are present, the shorter the cavity length at which  $I_{\text{th}}$  starts increasing.

### C. Laser Spectra

Measuring the spectra of short lasers reveals an amazing phenomenon. For instance, the shortest laser ( $29\ \mu\text{m}$  long) having a ridge width of  $10\ \mu\text{m}$  starts lasing at  $70\ \text{mA}$  ( $\sim 23\ \text{kA}/\text{cm}^2$ ) at a wavelength of  $852\ \text{nm}$ . At higher current ( $120\ \text{mA}$  or  $40\ \text{kA}/\text{cm}^2$ ) an additional peak appears at  $826\ \text{nm}$ . The shape of the first peak changes with the current due to some shift of the modes. The intensity of the first peak is about  $9\ \text{dB}$  higher than the second one. Pushing the current further to  $130\ \text{mA}$  leads to a third peak at  $804\ \text{nm}$  [Fig. 7(a)–(c)]. The third peak intensity is again about  $10\ \text{dB}$  lower than the intensity of the second peak. This phenomenon of laser emission at multiple wavelengths started with a cavity length of  $75\ \mu\text{m}$  with the five-QW structure. It should be noted that

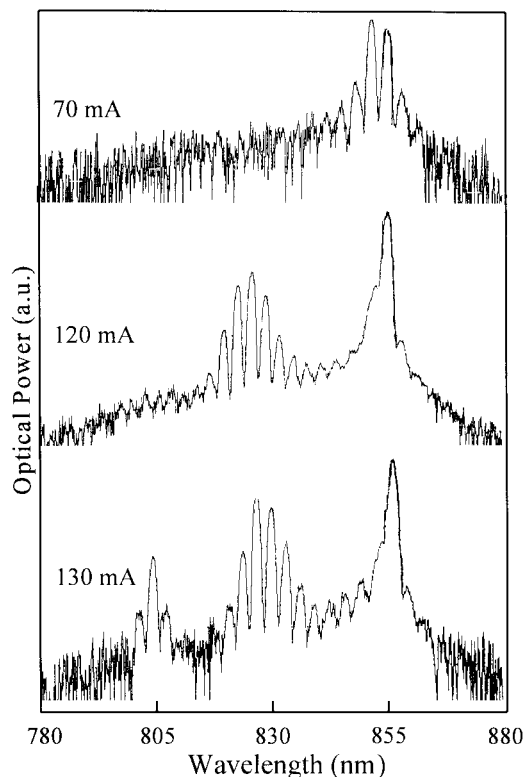


Fig. 7. Laser spectra of an etched laser 29- $\mu\text{m}$ -long 10- $\mu\text{m}$ -wide ridge at various currents.

these short lasers did not all emit at the same wavelengths: some devices emit at 848 nm and at about 795 nm (instead of 852 and 804 nm). This discrepancy was also found when measuring devices made from the two- or three-QW laser structures. Multiple peaked spectra were also obtained with even longer devices, i.e., 200  $\mu\text{m}$ . This phenomenon was completely absent in lasers with bulk active layers which emit at only one wavelength around 870 nm. A first conclusion can be drawn that multiple wavelength emission is related to higher order quantized states in QW structures.

Longer lasers (500 or 750  $\mu\text{m}$ ) emit light at one wavelength around 854 nm even when increasing the current up to 400 mA ( $\sim 5 \text{ kA/cm}^2$ ). This suggests that the light emission at more than one wavelength is related to high current injection. A point of attention is the threshold current density  $J_{\text{th}}$ : lasers having a cavity length of 300  $\mu\text{m}$  or more had a threshold density of the order of 400  $\text{A/cm}^2$  which is comparable to values obtained with cleaved lasers, while short lasers have much larger threshold densities of 10  $\text{kA/cm}^2$  or even higher.

Another observation is that some short devices showed laser operation only at a wavelength around 800 nm which corresponds to the  $n = 2$  transition.

To help understand this spectral behavior, photoluminescence (PL) and electro-reflectance (ER) measurements were performed on the five-QW laser structure. ER involves the direct detection of the small change in reflected light intensity that occurs when an electric field is applied across the structure. Our justification for using this approach is the fact that ER, more sensitive than other modulation techniques, yields rich and sharp spectral structures. For the ER measurements, a 20-

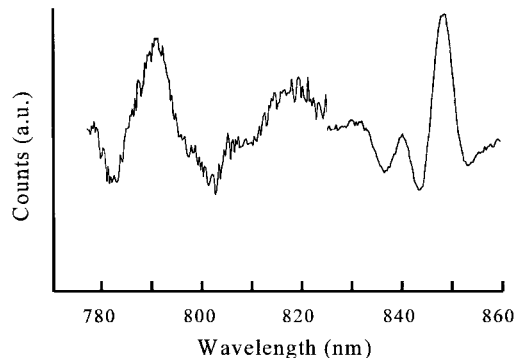


Fig. 8. ER spectra of the five-QW GRINSCH structure.

TABLE I  
OVERVIEW OF ELECTRON AND HOLE SUBLEVELS

$E_p$	E1	E2	HH1	LH1	HH2	LH2
1.424	0.0451	0.13764	-0.01139	-0.03072	-0.04409	-0.0942

TABLE II  
RESULTING TRANSITIONS IN NANOMETERS

Allowed transitions			Forbidden transitions			
E1-HH1	E1-LH1	E2-HH2	E1-HH2	E1-LH2	E2-HH1	E2-LH1
840 nm	829 nm	773 nm	821 nm	801 nm	788 nm	778 nm

nm evaporated  $\text{Cu}_2\text{S}$  layer was used as a transparent electrode [7]. Silver paste provides an ohmic contact to the  $n^+$  GaAs substrate. The experimental apparatus is described in [8].

The PL showed two peaks at 844 and at 835 nm corresponding probably to the  $n = 1$  transitions (E1 with HH1 and LH1). The ER measurements reveal four peaks at 848, 840, 819, and 792 nm (see Fig. 8). While the first two peaks can be attributed to the  $n = 1$  transition involving E1 with heavy holes 1 (HH1) and light holes 1 (LH1), and the last peak to the  $n = 2$  transition (E2-HH2), the third peak remains mysterious.

Moreover, polarization-dependent measurements pointed out that all peaks are TE-polarized.

#### D. Discussion

Calculations of energy subband levels of a 7-nm GaAs QW were performed using the standard effective mass formalism assuming 60% of the bandgap discontinuity in the conduction band. Table I gives an overview of the different electron and hole sublevels in electronvolts with respect to the conduction and the valence band, respectively. Table II shows the resulting transitions in nanometers.

Complex spectral behavior has been reported by Zory *et al.* [9], Mittelstein *et al.* [10], and by Tokuda *et al.* [11]. In [9], the authors obtained up to two wavelengths in short (155- $\mu\text{m}$ ) cleaved lasers. They showed that the transition from the higher to the lower wavelength is temperature-dependent and the two peaks occur simultaneously in a narrow range of temperature (58  $^\circ\text{C}$ –60  $^\circ\text{C}$ ). This phenomenon was obtained in a GRINSCH structure with a 50- $\text{\AA}$ -thick SQW of GaAs active layer, while lasers from a DHS structure show laser operation only at one wavelength. They invoke higher level subband

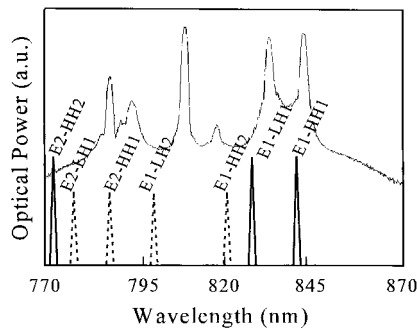


Fig. 9. Comparison between an experimental laser spectrum of an etched laser ( $L = 100 \mu\text{m}$ ) at 120 mA and calculated transitions where solid and dashed lines represent allowed and forbidden transitions, respectively.

transitions to explain these results where the emission at 820 nm is attributed to the  $n = 1$  transition and the second peak at 770 nm to the  $n = 2$  transition. The  $n = 2$  transition was found to be the weakest of the two. Mittelstein and Tokuda showed that SQW lasers with high resonator losses, by varying the cavity length, lead to a sudden jump in the laser wavelength which corresponds to a change from the fundamental transition to the second quantized state ( $n = 2$ ). This occurs at a modal gain of  $\leq 100^{-1}$  corresponding to a cavity length of about  $125 \mu\text{m}$  [10], while Tokuda found the same transition in the lasing mode at a cavity length of  $200 \mu\text{m}$  [11].

Concerning our experimental results, we can attribute the first peak (around 847 nm) to the  $n = 1$  transition (E1-HH1) and the peak around 800 nm to the  $n = 2$  transition (E2-HH2). The middle peak at about 825 nm is too far from the  $n = 1$  transition involving the light holes and is very close to the calculated forbidden transition E1-HH2. The ER measurements confirm the presence of a peak in the vicinity of 820 nm. Combining these two aspects, we believe that this peak, around 825 nm, encountered several times in our results, is probably related to the forbidden transition (E1-HH2). The only explanation of this strange result would be caused by the high current density in the short lasers which is about  $40 \text{ kA/cm}^2$  when observing two or three peaks in the spectra. This high current injection would break the normal parity in the bandgap, creating an overlap in the wavefunction and thus allowing the E1-HH2 transition.

To conclude this discussion, Fig. 9 shows a peculiar spectrum of an etched laser,  $100 \mu\text{m}$  long and  $10 \mu\text{m}$  wide at 120 mA, totaling six peaks. All calculated transitions including the forbidden ones are equally shown.

#### IV. CONCLUSIONS

In Section II, we presented a versatile etch technique to fabricate wet-etched mirror lasers. This technique has been applied as well to DHS structures as to GRINSCH structures with QW active regions. CW laser operation was reported in QW GRINSCH structures. In Section II, we presented the complex spectral behavior of wet etched short lasers where laser operation at more than one wavelength was very common. The multiple peaks are related to higher order transitions in the QW structures. Laser operation at a forbidden transition

appears to have been encountered. To our knowledge, this is the first time that such a result is reported.

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**E. Smalbrugge**, photograph and biography not available at the time of publication.

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**S. Gaillard**, photograph and biography not available at the time of publication.

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