InGaAs/GaAs quantum well lasers with dry-etched mirror passivated by vacuum atomic layer epitaxy

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We report measurements of strained InGaAs/GaAs quantum well laser diodes with electron cyclotron resonance (ECR) plasma etched mirrors that are passivated and smoothed with a novel technique involving the selective area growth of GaAs by vacuum atomic layer epitaxy. The threshold current of as-cleaved, etched, and passivated devices has been studied and a significant improvement in mirror feedback is shown with the passivation and smoothing of etched mirrors oriented along the [001] planes.

Etched mirrors for semiconductor laser diodes are needed for optoelectronic integration where monolithic placement of several lasers, waveguides, couplers, and transistors in a single opto-electronic integrated circuit (OEIC) is desired. Anisotropic dry-etching techniques such as reactive ion etching (RIE), ion milling (IM), and reactive ion beam etching (RIBE) have been investigated.[1] However, these processes owe a considerable part of their anisotropy to the physical etching caused by an intense ion bombardment that results either from the explicit nature of the process, as in the case of the last two techniques, or from the rf induced self-bias in the RIE case. In the presence of this physical etching, surface damage and roughness is expected and a degradation of mirror feedback can result. An alternative, potentially less damaging, dry-etching technique utilizes ECR plasma etching in which a GHz microwave source and high magnetic field confines electrons and efficiently ionizes the etchant gases with a much smaller plasma self-bias.[2] Results of preliminary work using this approach encourage us to employ ECR to etch high quality mirrors.[3]

In this letter we report passivation of ECR defined mirrors by growth of thin GaAs layers using vacuum atomic layer epitaxy (V-ALE).[4] We show that V-ALE, which is a low-temperature, highly selective, and monolayer-controllable technique, is well matched to our purpose. The refractory metal tungsten is used both as a self-aligned contact and as a selective area growth mask. The tungsten process is compatible with existing very large scale integration (VLSI) metal insulator semiconductor field effect transistor (MISFET) technology and hence suitable for OEIC applications.

In this work we investigate several laser diodes fabricated from the same wafer. The laser diode structure consists of a strained InGaAs/GaAs single quantum well graded index separated confinement heterostructure (GRINSCH) grown epitaxially by metalorganic chemical vapor deposition (MOCVD) on a (100)-oriented substrate. The epitaxial layers are shown in Table I. The quantum well is designed and measured to provide gain in the wavelength range between 0.92 μm$<\lambda<$1.01 μm and below 0.92 μm for $n=1$ and $n=2$ transitions, respectively.

Following epitaxial growth the sample was removed from the growth chamber and a 1000-Å-thick electron-beam evaporated tungsten layer was deposited over the wafer. 50-μm-wide stripes separated by 250 μm were photolithographically defined and excess tungsten dry etched in a CF_4 plasma. The devices were then isolated using ECR etching in chlorine gas to remove the p^+-doped GaAs cap layer between the tungsten metal stripes. Next, the sample was photolithographically patterned and a 5-μm-deep ECR etch resulted in vertical mirror faces. Figure 1 shows a scanning electron microscope (SEM) micrograph of the as-etched mirror. The cavity length of the laser is $L_C=200$ μm.

Passivation and smoothing of the mirrors is achieved using selective area growth in a V-ALE chamber described elsewhere.[4] In this experiment the tungsten stripes are used to mask epitaxial growth. The substrate was heated up to 620 °C for thermal cleaning and then cooled down to 530 °C for the growth sequence. The process cycle consists of trimethylgallium (TMGa) injection for 0.2 s followed by 4 s pumping, 2 s tertiarybutylarsine TBAs injection, and 2 s pumping. The exposure levels of TMGa and TBAs were 0.8×10^{-6} and 8.6×10^{-6} mole/s, respectively. This cycle was repeated 40 times to result in the growth of approximately 300 Å of GaAs on a (100) plane.

Finally, low-resistance ohmic contact metallization is achieved using electroplating. First the back side is plated with Au/Sn and alloyed in H_2 atmosphere for 15 s at 420 °C. Following this, the tungsten stripes and the back n-type con-

TABLE I. Layer structure for the lasers used in this study.

Material	Thickness (μm)	Impurity concentration (cm^{-3})
GaAs	0.1	$p=5\times10^{18}$
$Al_{0.5}Ga_{0.5}As$	1.5	$p=5\times10^{17}$
$Al_{0.5}Ga_{0.5}As$-$Al_{0.3}Ga_{0.7}As$ grade	0.2	i
GaAs	0.0150	i
$In_{0.2}Ga_{0.8}As$	0.0095	i
GaAs	0.0150	i
$Al_{0.3}Ga_{0.7}As$-$Al_{0.5}Ga_{0.5}As$ grade	0.2	i
$Al_{0.5}Ga_{0.5}As$	1.5	$n=5\times10^{17}$
GaAs	0.2	$n=2\times10^{18}$
GaAs	Substrate	$n=2\times10^{18}$

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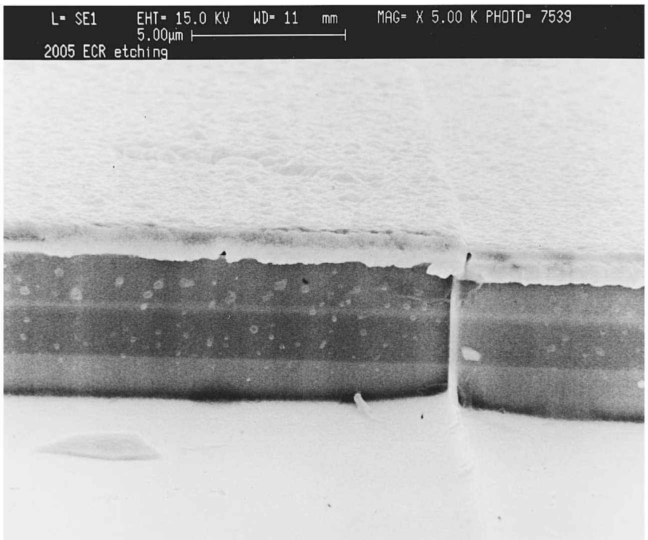

FIG. 1. SEM micrograph of the ECR etched laser mirror. The Au plated W contact layer is visible to the left of the image.

tact are plated with a thick Au layer. The series resistance of completed devices is less than 3 Ω at $I=I_{th}$.

As a reference, part of the same wafer was also processed with conventional cleaved mirrors along [011] planes. Threshold current versus cavity length along with the measured emission wavelength range for these cleaved devices is shown in Fig. 2(a). As commonly observed in this type of gain medium, the threshold current increases rapidly for $L_C<400$ μm. In this range, as the cavity length reduces, the laser threshold becomes more dependent on the mirror losses. The needed increase in peak gain results in laser emission at shorter wavelengths. Using the logarithmic gain approach a transparency current of 152 A/cm^2 at $\lambda=1$ μm is estimated from this data. This good material quality indicates that laser performance is determined primarily by device processing issues.

We investigated the influence on mirror feedback with etched, passivated, and conventional cleaved mirrors for $L_C=200$ μm. This relatively short cavity length ensures that laser threshold current is sensitive to mirror quality [see Fig. 2(a)]. Table II summarizes our results. Lasers with conventional cleaved mirrors exhibit an $I_{th}=85$ mA ($J_{th}=0.85$ kA cm^{-2}) current threshold with emission wavelength at $\lambda=0.94$ μm. The current threshold after ECR etching mirrors shows an average value of around $I_{th}=150$ mA ($J_{th}=1.5$ kA cm^{-2}) indicating mirror degradation. Comparing this degradation with that caused by other dry-etching techniques is inappropriate because previously published results use either longer cavity devices, cleaved-etched hybrid structures, post-etching passivation, and/or dielectric coatings.[5,6] With the V-ALE passivation of ECR etched samples with mirrors aligned in the [011] plane we observe a further increase in threshold to around $I_{th}=180$ mA ($J_{th}=1.8$ kA cm^{-2}) while after V-ALE regrowth on the [001] mirrors an improvement in current threshold is achieved. Threshold current as low as $I_{th}=97$ mA ($J_{th}=0.97$ kA cm^{-2}) is obtained in the latter case

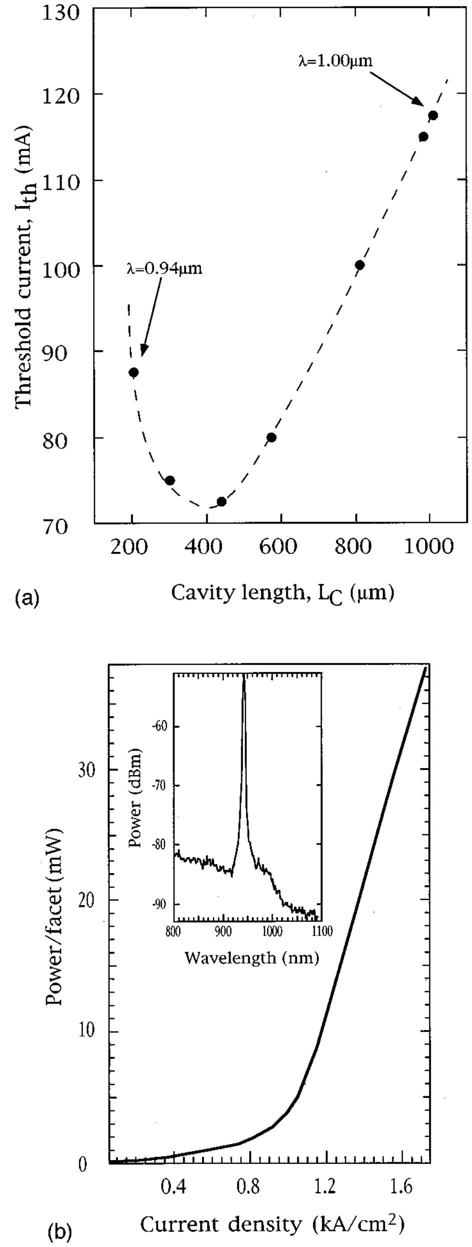

FIG. 2. (a) Room-temperature threshold current vs cavity length for lasers with cleaved mirrors. The lasing wavelength is shown for $L_C=200$ μm and $L_C=1000$ μm. The laser stripe width is 50 μm. (b) Room-temperature L-I characteristic for a laser with ECR etched mirrors and V-ALE passivation along the [001] crystal planes. $L_C=200$ μm and stripe width is 50 μm. The inset shows the laser spectrum measured for a drive current of $I=2I_{th}$. Optical emission peaks at wavelength $\lambda=0.94$ μm and spectrometer resolution is 5 nm.

TABLE II. Average room-temperature threshold current and threshold current density for lasers at different stages of processing.

	Threshold current I_{th} (mA)	Threshold current density (kA/cm^2)
As cleaved	85	0.85
ECR etched	150	1.50
ECR etched plus passivation [011]	180	1.80
ECR etched plus passivation [001]	97	0.97

(a)

(b)

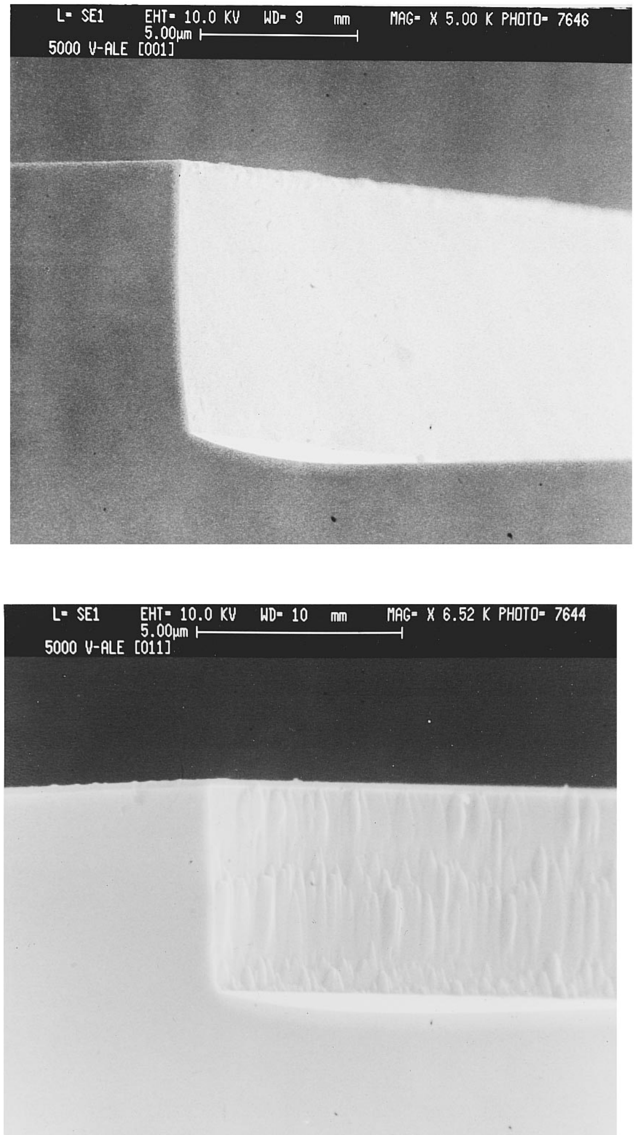

FIG. 3. SEM micrographs showing V-ALE growth morphology on vertically etched GaAs mirrors; (a) mirror in the [001] crystal plane, (b) mirror in the [011] plane.

indicating a reflectivity very close to the cleaved mirror value. Figure 2(b) depicts typical light-current (L-I) characteristics for the lasers with [001] passivated mirrors. The inset in Fig. 2(b) shows the lasing spectrum at current $I=2I_{th}$ with peak emission at wavelength $\lambda=0.94$ μm.

The degradation observed for dry-etched mirrors aligned along conventional [011] cleave planes is probably a result of the strong crystal orientation dependence on surface reaction in ALE growth. It is this dependence which helps create a high spatial growth selectivity when using the tungsten stripe as a growth mask. On the other hand, the growth characteristics in crystallographic planes of different chemical nature is severely affected. While [001] planes are single atomic planes with more stable double bonds connecting the arriving As atoms to the Ga plane, [011] planes have 50% As and 50% Ga with the As atoms of a layer being weakly adsorbed by a single bond. High As desorption and consequently slow ALE growth rate results in the [011] planes as demonstrated by Isshiki *et al.*[7] Therefore, given an etched [011] mirror, ALE growth will tend to occur more readily on the exposed [001] surfaces associated with roughness of a nonperfect etch. In this situation three dimensional defects are enhanced. For growth on the etched [001] plane the opposite is expected with the [011] surfaces associated with roughness being suppressed by V-ALE growth such that both good passivation and good smoothing is obtained. To verify the growth morphology in these two planes we grew a 5000 Å layer by V-ALE on samples etched along these two orientations. The SEM image in Fig. 3(a) shows the smooth growth that results in the [001] planes after the ALE growth. Figure 3(b) shows the growth for the [011] plane where the enhancement of the etching defects and consequent surface roughness is evident.

In conclusion, the performance of InGaAs/GaAs quantum well Fabry–Pérot lasers with ECR etched mirrors can be significantly improved by using selective V-ALE growth to passivate and smooth the mirrors. Improved mirror smoothing and passivation is found to occur on [001] crystal planes while surface roughness increases on [011] planes.

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