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Assessing plasma-etched InP laser facet quality

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***Abstract*—This work presents an approach to assess the quality of etched laser facets, considering factors such as roughness, inclination, and non-uniform light emission. Broad area InP lasers, using plasma etched facets, operating at 1550 nm are manufactured with varying facet quality on five 100 mm wafers. Comparison of the threshold current density of lasers of different length was used to derive relative facet reflectivity and demonstrated the relationship between the reflectivity and the optical mode weighted facet roughness and facet inclination.**

***Index Terms*—Optoelectronic Integration, InP Lasers, Etched Facets.**

I. INTRODUCTION

TRADITIONALLY semiconductor laser facets are produced by cleaving the crystal to obtain a smooth surface perpendicular to the laser emission. Some materials such as Gallium Nitride (GaN) have a crystal structure that does not naturally cleave in the required manner [1]. As a result, manufacturing etched facets in these materials is more established [2]. Etched reflectors are becoming more important in semiconductor laser manufacture, even for materials that easily cleave, as they are positioned via optical lithography, rather than the less precise cleave initiation, and this can improve yield [3]. In addition, lasers fabricated as part of large area optoelectronic monolithically integrated circuits cannot use cleaved facets, and high quality etched reflectors facilitate integration without regrowth. Wet etching is unsuitable due to the inability to reliably produce the vertical profiles required, whereas dry plasma etching overcomes these issues using methods preferred in large scale manufacture. Dry etching does tend to introduce an increased roughness to the laser facet and other vertical surfaces/sidewalls [4]. The process parameters that control surface roughness are linked to other etch properties and can be optimised to minimise roughness, provided the relationship between surface roughness and performance is known. However, the impact of roughness on facet reflectivity and thus device performance is yet to be fully understood, and there is no widely adopted methodology to determine the quality of a laser facet. While measurements such as facet inclination can be obtained from Scanning Electron Microscope (SEM) images, it is but one factor in facet quality that impacts reflectivity [5]. Surface roughness is another key factor determining facet reflectivity but is difficult to measure. By definition the RMS surface roughness, which has been used, is reporting the average roughness across the sampled area [6], therefore if the facet contains regions of localised roughness in key locations, or the methodology that defines this sampled area differs between measurements, any comparisons may not be representative.

There are reports of how the facet reflectivity depends on surface roughness and this has been shown to work for some situations and materials [7]. Equation 1 takes account of the different phase of light reflected from different point sources over a Gaussian distribution of depths. $R(\Delta d)$ is the reflectivity of a facet with an RMS roughness of Δd, R_0 the reflectivity of a perfectly flat facet, n the refractive index of the material, and λ_0 the emission wavelength in a vacuum

$$\frac{R(\Delta d)}{R_0} = \exp\left[-16\pi^2\left(\frac{n\Delta d}{\lambda_0}\right)^2\right]. \tag{1}$$

In other materials or where structures are more varied and are required for larger wafer sizes, dry etching is more challenging and the model fails to describe the quality of the facet achieved. Here we aim to develop an approach, that builds on [7], that describes the quality of dry etched facets for more challenging materials such as InP, allowing for easier optimisation of a manufacturing process.

II. DEVICE FABRICATION

The InP epitaxial structures grown via MOCVD used in this work comprise of six compressively strained InGaAsP quantum wells, typical of InP laser structures, set in an InGaAs waveguide core within InP cladding layers and designed to emit at 1550 nm. To simplify fabrication and allow focus on the etched facet reflectivity a relatively simple laser structure is selected. A broad area laser, minimises any impact the sidewall roughness would have in a narrow ridge device, isolating the impact of surface roughness to the facet alone. While these structures differ from those typically used, in e.g. datacom applications, they will provide findings that can be applied to more complex structures.

Our approach to understand the impact of the etch process on facet reflectivity will use a comparison of lasers with etched

Device fabrication was conducted at the KLA Corp (SPTS Division) site in Newport, South Wales and in the cleanroom of the ERDF-funded Institute for Compound Semiconductors (ICS) at Cardiff University with assistance from both KLA and ICS staff. This work was supported by the Engineering and Physical Science Research Council EP/S024441/1, UKRI CS Strength in Places Fund (107134), along with KLA. Additionally, this work was also supported by the Henry Royce Institute for advanced materials through the Equipment Access Scheme enabling access to the Department of Materials Science at Cambridge; Cambridge Royce facilities grant EP/P024947/1 and Sir Henry Royce Institute - recurrent grant EP/R00661X/1.

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facets to those with cleaved facets. We describe the fabrication of the lasers where devices with etched facets are immediately adjacent to devices with cleaved facets.

The broad area laser cavities have a ridge width of 200 μm with cavity lengths ranging between 100 $\rightarrow$ 1000 μm. A 1 μm thick SiO_2 hardmask was used for the InP plasma etch and patterned using contact lithography. The single InP deep plasma etch was performed on an SPTS Inductively Coupled Plasma (ICP) etch tool using a Chlorine (Cl)-based chemistry. Finally coplanar contacts were deposited. To minimize any damage to the laser facets that may occur from removing the insulating SiO_2 hardmask layers, the facet is first protected with a photoresist while a small section of the hardmask is removed. The p-contact is then deposited into this hole making contact with the upper most layer of the device structure. This process was repeated with five separate 100 mm InP epi-layer wafers using slightly different etch processes to intentionally obtain a range of facet roughnesses and quality.

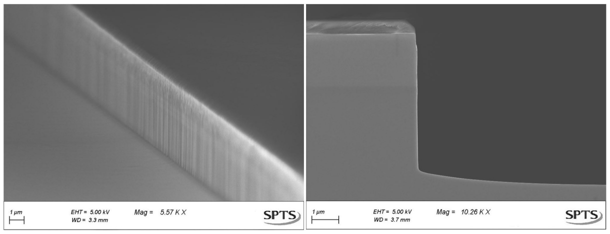

Fig. 1. (Left) SEM image of a plasma etched laser facet. (Right) SEM image of the etch profile showing an etch depth >4.2 μm and a flat vertical sidewall.

III. METHODOLOGY

The roughness of the laser facets was measured using a Bruker Dimension Icon Atomic Force Microscopy (AFM) tool using the peak force tapping ScanAsyst imaging mode. Device samples are mounted at an inclination with the AFM scan dimensions set to 4 μm $\times$ 4 μm, in order for the probe to sample the entire height of the facet. Etched facets often do not display a uniform roughness across the surface due to a number of factors including manufacturing defects such as mask recession, and the varying materials introduced in the epi-layer structure. As a result the reported RMS roughness of an etched facet can be easily manipulated by adjusting the area and location being sampled. Therefore, a fixed methodology to determine the sampled area was set and adhered to for all measurements. The sample area was set to 4 μm $\times$ 2.2 μm with the midpoint focused on the device epi-layers, so that the area overlaps with that containing the majority of the emitted laser light. A 4 μm width was selected to account for the entire width of the scanned AFM image. The location sampled on the facet was a randomly selected region at least 5 μm from the facet edge, where the sidewall surface was consistent across the facet. The 2.2 μm height comes from a 6σ deviation in the calculated vertical nearfield distribution. As the sampled region focuses on the epi-layers, where the peak of the vertical nearfield occurs it ensures that the sampled area includes over 99% of the light that interacts with the facet, while not considering regions on the facet that will have little to no impact on the reflectivity.

Following the AFM measurements the samples were lapped in order to reduce the material thickness and produce a high quality cleave for those lasers that would have cleaved facets. Due to the wafer bow and material fragility, achieving thicknesses below 150 μm proved difficult. It is often suggested that in order to manufacture a high quality facet the cavity length can be no shorter than two and a half times the material thickness. Therefore, cleaved facets of devices with cavity lengths below 375 μm were expected to be of a lower quality. All cleaved facets were optically inspected under a microscope at 50x magnification and any devices with clear facet damage were discarded. A sample of cleaved facets were analysed using AFM measurements and displayed a highly uniform surface roughness of <0.3 nm, approximately half that of the lattice constant of InP. Therefore, they can be considered as atomically smooth.

The etched and cleaved facet devices are then extracted, mounted and wire bonded ready for characterisation. Pulsed optical power versus current (PI) and current-voltage (IV) measurements were taken at a controlled temperature of 21°C for both etched and cleaved facet devices. Using the PI measurements the threshold current for each device can be determined using the maximum observed in the second derivative. Finally, plotting the inverse cavity length against the threshold current density results in a linear trend where the gradient (m) is proportional the reflectivity of the two facets (R_1 and R_2) [8]

$$m \propto \ln\left(\sqrt{\frac{1}{R_1 R_2}}\right). \tag{2}$$

As the cleaved facets are considered to be atomically smooth the reflectivity of these facets can be calculated using the refractive index of the material and surrounding medium. Using this the proportionality constant (k) for the material can be determined. Given that both the etched and cleaved devices use the same material the proportionality constant can be substituted back into equation 2, allowing the average etched facet roughness (R_{ave}) to be determined using the gradient of the etched facet relation (m_{EF})

$$R_{ave}^2 = \exp\left(\frac{-2m_{EF}}{k}\right). \tag{3}$$

IV. RESULTS AND DISCUSSION

Fig.2 shows the relation between threshold current density and inverse cavity length for both etched and cleaved facet devices for one of the wafers. The etched facets display a steeper gradient corresponding to a lower facet reflectivity. Repeating this process for each of the remaining wafers allows for the relation between facet roughness and reflectivity to be determined, as seen in Fig.3.

The surface roughness of the etched facets, as measured by AFM, is in line with what can be expected from a plasma etch process, with the potential to obtain smoother facets with further process optimisations. The results presented in Fig.3 do not suggest clear relation between the surface roughness and

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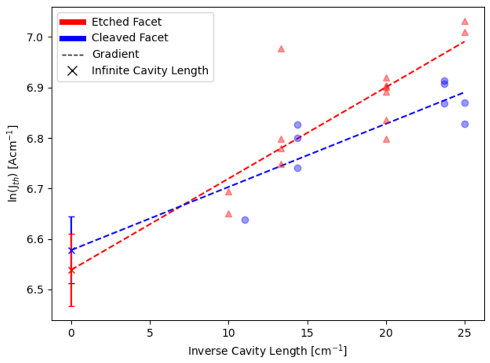

Fig. 2. Threshold current density of both etched and cleaved facet devices plotted against the inverse cavity length. Cleaved facets are marked with blue circles and etched facets with red triangles.

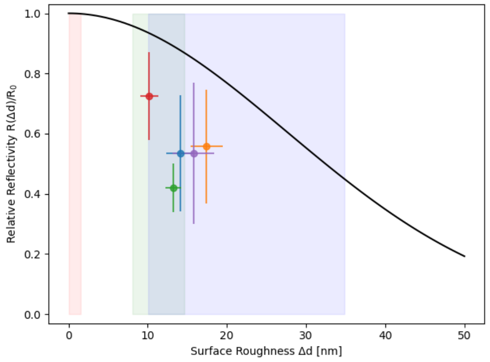

Fig. 3. Facet reflectivity plotted against the RMS surface roughness of the facet for each of the five device wafers. Moving from left to right the shaded areas indicate the expected RMS roughness of a facet manufactured via cleaving (red), plasma etch followed by a wet etch polish (green), and a plasma etch alone (blue). The relation described by equation 1 is shown with the solid black line [5], [9], [10].

reflectivity of a facet, with all facets returning a reflectivity lower than that calculated using equation 1 [7]. When taking a surface roughness measurement, a mean plane is defined as running through the surface topology, the RMS roughness calculation then considers deviations from this plane. As a side effect of this approach, all indication of facet inclination is lost, which can have a significant impact on reflectivity with an inclination of only a few degrees resulting in over a 50% drop in facet reflectivity (Fig.5). By using a surface roughness measurement the mean plane used in the RMS calculation may not lie perfectly perpendicular to the axis of light emission. If the etch profile and thus facet inclination is not perfectly vertical any additional losses from the inclination are not being accounted for. Adjusting the RMS surface roughness calculation to restrict the mean plane to be perpendicular to the axis of light emission the “facet roughness” can be determined as illustrated in Fig.4.

An RMS surface roughness measurement is ideal for determining how rough a surface is when optimising facet roughness. However, when considering laser facet quality, inclination also has a significant impact on reflectivity and thus both surface topology and inclination must be considered.

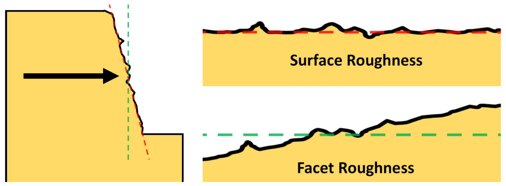

Fig. 4. Illustration of (Left) an exaggerated etch profile with a non-perpendicular facet inclination. Arrow indicates the axis of light emission, red dashed line is the mean plane of the surface roughness, dashed green line is the mean plane restricted to be perpendicular to the axis of light emission, determining the facet roughness. (Right) how restricting the mean plane to be perpendicular to the axis of light emission can introduce additional deviations from the mean plane, increasing the non-ideality of the facet.

Fig.5 illustrates how altering the facet inclination can impact the reflectivity of a facet despite the surface roughness remaining unaltered. It is important to note that the facet roughness is no longer representative of a surface roughness, it combines the impact from both surface roughness and inclination to better represent the interface the light experiences when being emitted from the device.

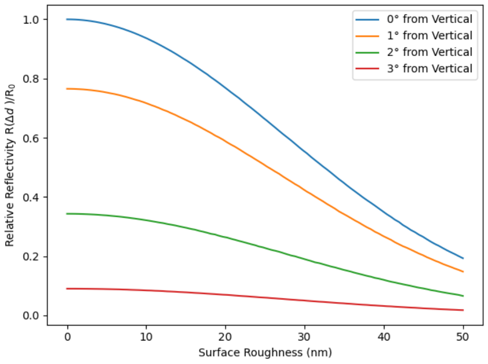

Fig. 5. Plot of the relative reflectivity of a facet against the surface roughness as described by equation 1, and how this relation changes when using the facet roughness as the inclination drifts from being perfectly vertical.

Fig.6 shows the relation between facet reflectivity and the facet roughness. While the facet roughness is a much better measure of facet quality than the surface roughness alone and a clear trend is visible, facet reflectivity calculated from the laser measurements are slightly lower than that predicted by equation 1. At this point we consider that light is not emitted uniformly across the facet. Not every point on the facet should have an equal impact on the reflectivity experienced by the laser. In these simple broad stripe devices, the light emission in the lateral dimension is fairly invariant. However, in the vertical dimension the light intensity is governed by the single mode waveguide.

By calculating the vertical nearfield distribution we can determine how much of the emitted light is interacting with a particular region of the laser facet. The vertical nearfield distribution for the devices used in this work shows an approximately Gaussian distribution centered on the device epi-layers. Therefore, any roughness near the epi-layers will be interacting with a much greater portion of the light. Consequently these regions will be more critical, and any roughness here will

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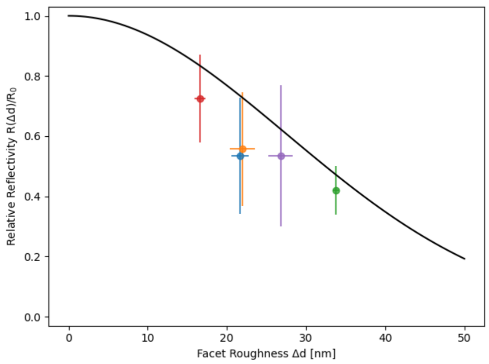

Fig. 6. Facet reflectivity plotted against the facet roughness, which accounts for a facet inclination. The relation described by the equation 1, using the facet roughness as the input Δd, is shown with the solid black line.

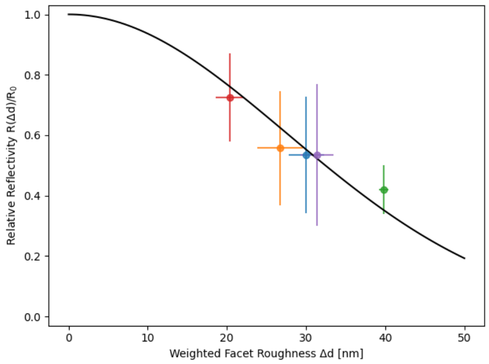

Fig. 7. Facet reflectivity plotted against the weighted facet roughness, which accounts for a facet inclination and the non-uniform emission of light. The relation described by equation 1, using the weighted facet roughness as the input Δd, is shown with the solid black line.

have a larger impact on facet reflectivity. Using the calculated vertical nearfield distribution, the facet roughness can be weighted to account for the non-uniform emission of light from the surface and emphasise roughness in device critical regions.

Fig.7 displays the relation between facet reflectivity and the weighted facet roughness, accounting for both facet angle, as measured from SEM imaging, and the calculated nearfield profile of light. Performing these additional steps of data processing, the experimental results obtained from the InP broad area lasers come into agreement with the relation predicted by equation 1.

When manufacturing etched facets it is common to optimise based on an RMS surface roughness target. The results presented here demonstrate that for more challenging etching work, the RMS surface roughness is not a suitable target and both the inclination (or facet roughness as defined here) and the location of the roughness relative to the laser field profile should be taken into account. In practice when dry etching it is often the case that the facet roughness and inclination are highly intertwined and improving the quality of one can increase imperfections in the other. Additionally, particular deficiencies in the etching process can cause highly localised roughness and these may or may not be important to device performance. Thus, knowledge of the device design is important to fully optimise etching processes. Weighted facet roughness as described here considers all these variables with a single value and allows for an accurate facet reflectivity to be determined and optimised.

V. CONCLUSIONS

In this work we have shown that a surface roughness measurement alone is not able to provide an accurate description of the quality or reflectivity of an etched laser facet. While surface roughness measurements can provide very useful information about the facet topology, it does not account for facet inclination or any localised roughness at critical regions on the facet. By implementing a weighted facet roughness measurement we can account for these factors, producing a clear relation between facet quality and reflectivity. This is achieved by restricting the mean plane used in RMS roughness calculations to be perpendicular to the axis of light emission from the facet, and weighting the deviations from the mean plane by the vertical nearfield distribution. The nearfield distribution has also been shown to be useful for defining the regions on the facet that should be sampled for facet quality measurements. This work extends the model previously proposed by D. A. Stocker et al. and other aproaches [7], [11] to more challenging etching scenarios. Utilising the weighted facet roughness also allows for a clearer idea of how each of the key factors impact reflectivity, which can be very useful for manufacturing process optimisation. When applying this methodology of determining the facet quality of more complex laser structures, particularly narrow ridge devices, it may be necessary to also consider the horizontal nearfield distribution.

VI. DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available upon reasonable request from the authors.

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