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Surface defects in semiconductor lasers studied with cross-sectional scanning tunneling microscopy

R.J. Cobley*, K.S. Teng, M.R. Brown, P. Rees, S.P. Wilks

Multidisciplinary Nanotechnology Centre, School of Engineering, Singleton Park, Swansea, SA2 8PP, UK

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ABSTRACT

Cross-sectional scanning tunneling microscopy is used to study defects on the surface of semiconductor laser devices. Step defects across the active region caused by the cleave process are identified. Curved blocking layers used in buried heterostructure lasers are shown to induce strain in the layers above them. Devices are also studied whilst powered to look at how the devices change during operation, with a numerical model that confirms the observed behavior. Whilst powered, low-doped blocking layers adjacent to the active region are found to change in real time, with dopant diffusion and the formation of surface states. A tunneling model which allows the inclusion of surface states and tip-induced band bending is applied to analyze the effects on the tunneling current, confirming that the doping concentration is reducing and defect surface states are being formed.

1. Introduction

Cross-sectional scanning tunneling microscopy (X-STM) on the unreconstructed (1 1 0) surface of semiconductor lasers gives a view across all growth layers in the devices. For defect free surfaces there are no mid-band gap surface states and the technique can be used to study surface morphology, cleave-induced defects, doping concentration, interface quality, atomic-level intermixing, potentiometry and surface passivation, amongst others [1–5].

Semiconductor lasers have a wide range of uses from optical communications to data storage [6]. Typical surface defects formed during production of these devices include steps, strain-induced changes, lattice disordering, intermixing at heterojunctions and dopant diffusion. These defects change the material properties and introduce mid-band gap surface states which detrimentally affect device performance and ultimately lead to device failure [7]. Surfaces of such optoelectronic devices are coated with layers of material which passivate these surface states by moving their bond energies out of the band gap [8–10].

Here X-STM is applied to the unpassivated (1 1 0) facet of semiconductor lasers to study a range of surface defects which affect device operation. Using a technique which allows devices to be powered whilst performing X-STM, devices are also studied whilst operating in real time, to look at defect generation and evolution [11,12]. Studying devices in this way is important to confirm that device designs operate as expected. This can only be done at this scale with a cleaved device, and in order to move towards qualitative data, the effect of the surface states needs to be better understood. These defects are also present in industrially cleaved devices prior to passivation. In order to understand how passivated surfaces affect device operation, it is important to first understand the role of defects on the surface of unpassivated surfaces.

This paper will look first at unpowered devices at rest to identify surface steps and strain. It will then look at performing X-STM on biased devices and the repeatable and reversible changes that occur in devices when studied in this way, along with a model which predicts the same changes. Finally low-doped regions near the active layers are found to undergo irreversible damage whilst under operation, due to dopant out-diffusion and surface defect state formation. The process is studied and modeled.

2. Experimental

Samples are cleaved *in situ* in a commercial ultra high vacuum system to expose a clean facet for investigation. Tips are made from electrochemically etched tungsten wire, cleaned *in situ* using high voltage pulses. The system has been modified to allow a potential to be dropped across the device being studied, independently of the

* Corresponding author. Tel.: +44 1792 602066; fax: +44 1792 602066.
E-mail address: richard.j.cobley@swansea.ac.uk (R.J. Cobley).

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applied gap voltage between the same sample and tip, all relative to a common ground point at one of the sample contacts. This allows the device to be powered whilst the scan continues.

Two types of laser device are used in this investigation: an AlGaAs/InGaAs double quantum well (DQW) structure, and an InP/InGaAsP buried heterostructure laser (BHL). More detailed information on the experimental procedure and device properties is given elsewhere [11,13]. The unreconstructed surface is expected to behave electrically similar to the bulk. Cleaving the device will have no effect on the electrical behavior [14] but will affect the operation of the optical cavity.

3. Numerical model

Two models are used to analyze the data which will be presented. The first uses a method based on Duke, as implemented by Feenstra [1,15]. A planar tunneling calculation is performed with no band bending in the sample surface, as a summation over all incoming states in k-space, with the calculated transmission factor for each state [11]. The full E-k bandstructure for each material is calculated using a local pseudopotential method based on that of Cohen and Bergstresser, implemented by Fischetti and Laux [16,17]. Energy diagrams for the devices under test were generated using a drift-diffusion model which fully coupled the electron and hole equations with Poisson's equation [18]. This gave the band profiles for both the sample at rest and showed how the devices behaved under bias.

A second tunneling model was used to more accurately study areas in the device which changed during operation. In low-doped materials the electrostatic potential of the scanning tip can induce depletion or accumulation layers in the sample being studied. Some of the applied potential between the sample and tip is dropped across this depletion region in which the sample bands bend. Here we use a second tunneling model by Feenstra which allows band bending at the surface and the inclusion of the discrete surface states formed by this potential variation. The profile of the tip-induced band bending is calculated by using Feenstra's SEMITIP3 which also allows the inclusion of surface defect states [19–23].

4. Results and discussion

The process of cleaving the laser wafer, used both in industry and research, can leave step defects across the facet, as shown in Fig. 1(a) for the BHL. Here, two levels of jagged step depression are visible across the otherwise atomically flat active region. The total measured depth is around 0.608 nm, slightly larger than the lattice constant of 0.587 due to surface relaxation [24].

Fig. 1(b) shows a larger image of the active region of the same device, with a gradient from the top of the image down towards the active region, culminating in depressions visible above the curved blocking layers. A plot along the marked line in that image is shown in Fig. 1(c). Shear force topographic images of the same device have shown that the origin of this gradient is not a physical height difference and therefore it must be an electronic effect [25]. Spectroscopy in this region confirms that the area is undergoing tensile strain [5]. The layers grown above the curved blocking layer are strained and relax out towards the surface producing the electronic effect visible with STM. Understanding how complicated confinement structures alter the material parameters and therefore device operation is crucial to optimizing these new devices.

Next we turn our attention to studying these devices whilst they are powered and active. Fig. 2 shows images of the DQW laser at rest and biased, and Fig. 3 the BHL. Electronic gradients exist across images due both to the change in contrast as the tip scans over the differently doped regions and materials, and because the sample is always physically tilted at this scale. As a bias is applied to the sample these electronic gradients, and the relative contrast of features in the image, change. However, the physical topography does not change and we can look at how a scan changes electronically simply by subtracting the image at bias from the image at rest. The STM images and line plots in Figs. 2(a)–(c) and 3 have had these gradients removed to show relative height. Fig. 2(d) and (e) however, show the change in this gradient across the image as the height change over the two micrometer length off the image (solid line), and overlay on top the change expected from the first model presented earlier (dashed line).

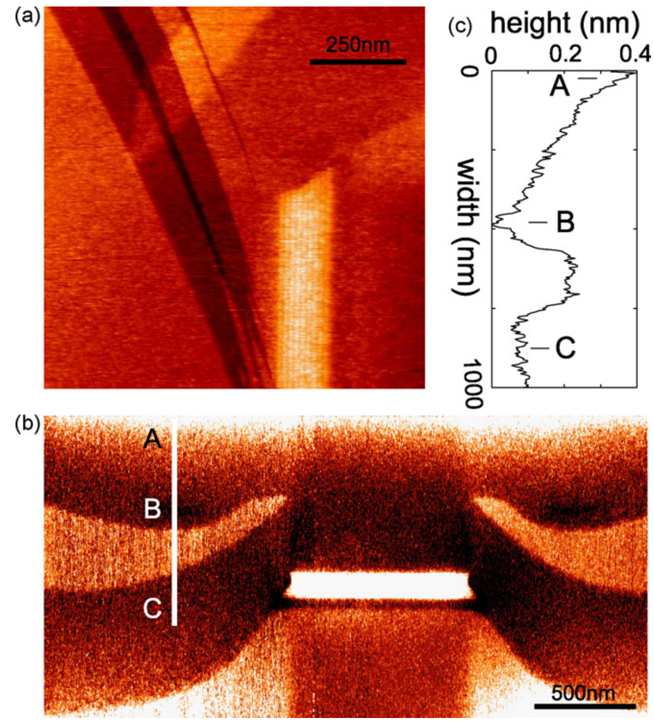

Fig. 1. STM images of the buried heterostructure laser (a) +2.2 V gap voltage, 0.3 nA, showing cleave-induced steps across the active region, (b) +2 V gap voltage, 0.5 nA with (c) the z-profile along the white line shown from A to C.

Electronic gradients and the relative contrast of features, such as the quantum well heights, are found to be reversible. The contrast in the image changes as power is applied to the device and then reduces back to the starting point when power is removed from the device. The magnitude of the change of gradients and features across an image is also consistent with the model. As seen in Fig. 2(d), at higher biases the model predicts slightly less change in the gradient due to model limitations in handling the optical behavior of the laser cavity.

With this standard pattern of behavior established, it is then possible to look at changes that occur on the surface of devices when they are left to run over a long period of time, or driven with higher currents [12]. One such change occurs in the low-doped regions that surround the quantum wells. An example for the BHL is shown in Fig. 4. The purpose of these low-doped layers is to prevent dopants in the higher-doped layers from diffusing in to the nominally undoped array of quantum wells and barriers. However in both devices these low-doped layers undergo permanent modification during operation. For the example in Fig. 4 when tunneling in to the BHL the p-type buffer appears brighter after modification whereas the n-type buffer appears darker.

This modification cannot be explained by a physical surface change, or by the formation of dark-area defects, because one layer increases in contrast as another reduces. Also when imaged with