GaAs-based superluminescent diodes with window-like facet structure for low spectral modulation at high output powers

O M S Ghazal¹, D T Childs¹, B J Stevens², N Babazadeh¹, R A Hogg¹ and K M Groom¹

¹Department of Electronic & Electrical Engineering, The University of Sheffield, Nanoscience & Technology Building, North Campus, Broad Lane, Sheffield, S3 7HQ, UK
²EPSRC National Centre for III-V Technologies, Department of Electronic & Electrical Engineering, The University of Sheffield, Nanoscience & Technology Building, North Campus, Broad Lane, Sheffield, S3 7HQ, UK

E-mail: k.m.groom@sheffield.ac.uk

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Abstract
We demonstrate a GaAs-based superluminescent diode (SLD) based on the incorporation of a window-like back facet into a self-aligned stripe structure in order to reduce the effective facet reflectivity. This allows the realisation of SLDs with low spectral modulation depth (SMD) at high power spectral density (PSD), without the application of anti-reflection coatings to either facet. This approach is therefore compatible with ultra-broadband gain active elements. We show that 30 mW output power can be attained in a narrow bandwidth, corresponding to 2.2 mW nm⁻¹ PSD with only 5% SMD, centred about 990 nm. We discuss the design criteria for high power and low SMD and the deviation from a linear dependence of SMD on output power, resulting from Joule heating in the self-aligned stripe.

Keywords: superluminescent diode, low reflectivity facets, semiconductor device fabrication

Superluminescent diodes (SLDs) offer relatively high power over a broad and smooth emission spectrum. Their waveguide structure enables far higher brightness than light emitting diodes and efficient fibre coupling, useful in many applications such as fibre-optic gyroscopes and optical coherence tomography. A key parameter defining the coherence properties of the SLD is the spectral modulation depth (SMD), which occurs due to Fabry–Perot modes arising from non-zero reflection at the facets of the device. Current methods to suppress this reflection rely on the use of anti-reflection (AR) coatings, which work to directly decrease the facet reflectivity. However, ultra-low reflectivity is difficult to achieve over broad bandwidths. Presently 100 nm is routinely required and hundreds of nm is desirable. An alternative method to reduce the effective reflectivity (describing light coupled back into the waveguide) is an angled waveguide.

Tilted facets, in which SLD waveguides are mis-oriented to the crystal-axis by an angle (typically 5°–10°) from the normal to the cleaved facet, suppress back reflection by deflecting reflected light outside the waveguide. This allows an effective facet reflectivity, $R_{eff}$, as low as $10^{-4}$. This is further reduced to $10^{-5}$ when also combined with an AR coating [1]. Transparent (window) regions can provide typical $R_{eff} < 10^{-3}$ [2]. In a traditional window structure, the waveguide is terminated and light is allowed to spread in an un-pumped region prior to the cleaved facet such that only a small fraction of the light is re-coupled back into the waveguide following reflection at the cleaved facet. Windows are inherently broad-band and can be combined with AR coatings.
and tilted waveguides to offer $R_{\text{eff}}$ below $10^{-5}$ \cite{3}. Furthermore, the use of absorbing sections to reduce $R_{\text{eff}}$ below $10^{-6}$ has been shown, using bent passive absorbers \cite{4, 5}, or grounded absorbers \cite{6}. With respect to ridge waveguide approaches, buried ridge or stripe methods allow for narrow active widths and control of carrier flow, reduced non-radiative recombination at exposed surfaces, and greater control of the optical beam profile allowing for improved coupling to fibre.

Biological applications require light penetration into highly turbid and absorbing tissue. The range of near-IR wavelengths accessed by GaAs based devices is ideally suited to this biological band \cite{7}. Typically, GaAs-based SLDs are realised using a combination of AR coatings and tilted facets. In addition, etched deflectors and long tapered absorbers have been demonstrated \cite{8}. However, only a limited number of reports have been made regarding window facets on GaAs devices. Window devices are commonplace on InP \cite{9}. However, it is difficult to directly transfer the window facet concept to GaAs due to the use of AlGaAs waveguide cladding and the requirement for regrowth upon exposed aluminium-containing layers in order to produce a buried waveguide. The application of window facets on GaAs has mainly been limited to non-interacting facets for raising the catastrophic optical damage threshold in high-power lasers \cite{10}, or have been realised using processes where aluminium-containing layers are exposed prior to overgrowth of the transparent window \cite{11, 12}. Such processes raise concerns over the long-term reliability of a growth interface on oxidised AlGaAs. Furthermore, alternative solutions comprising GaInP cladding lack design flexibility due to the limited range for which stoichiometry can be tailored and the smaller conduction band offset compared to AlGaAs cladding.

In this paper we present a new scheme for low $R_{\text{eff}}$ facets, based on the application of a self-aligned stripe regrowth process \cite{13}, to realise window-like structures in GaAs-based SLDs. We demonstrate low SMD from SLDs with no facet coating, making them naturally broadband. Our self-aligned stripe technology consists of a two-stage growth sequence in which GaAs/AlGaAs waveguide cladding layers are regrown upon a patterned GaInP optoelectronic confinement layer to form the structure shown schematically in figure 1(a), which provides both optical and electrical confinement. A transmission electron micrograph (TEM) is shown in (b), taken through the active stripe of this device. The position of the optical mode with respect to the waveguide is superimposed upon the TEM for illustration.
for illustration. By terminating the waveguide prior to the cleaved back facet, light is allowed to spread in the laterally unguided window region. However, in contrast to traditionally optically transparent window structures, the active region remains intact below the opto-electronic confining GaInP layer. Therefore light also undergoes absorption within the window-like region, resulting in further suppression of feedback into the waveguide and correspondingly lower $R_{\text{eff}}$. A plan view optical mode profile, simulated using FIMMPROP by Photon Design, is shown in figure 1(c) to illustrate the spreading of light in the window region.

The contrast between the modal refractive index in the stripe (3.284) and in the window region (3.281), calculated using FIMMWAVE by Photon Design, indicate $R_{\text{eff}} \sim 10^{-7}$, applying Snell’s law for a plane wave incident upon an abrupt interface. However, the real interface is not abrupt due to the angled regrowth interface resulting from the GaInP wet etch, and the output is collected from the waveguided facet. By terminating the waveguide prior to the cleaved facet and $J_{th}$ was recorded for devices as a function of increasing window length, $l$, until the point at which lasing could no longer be achieved. Using these values of $J_{th}$, conversion into $G_{th}$ allows an excess loss resulting from the window, $\alpha$, to be calculated as the windowed $G_{th}$—laser $G_{th}$. $R_{\text{eff}}$ is then determined from $R_{\text{eff}}^{\text{out}}$, where $R_{\text{cl}}$ is the reflectivity of the cleaved facet. $R_{\text{eff}}$ is plotted as a function of window length in figure 2(b). We can therefore conservatively suggest that $R_{\text{eff}}$ reaches $<10^{-11}$ at a window length of 2.25 mm. Tilting the waveguide with respect to the crystal axis can be expected to reduce $R_{\text{eff}}$ further. We note that at these very small values, the reflectivity of the transition region between the stripe and window-region may dominate in producing ripple and parasitic lasing.

For an ideal SLD (0% facet reflectivity and no self-heating) the output power can be related to the gain ($G$) and active length ($L$) as shown in equation (1) [15]. This describes an exponential dependence of power on gain, as demonstrated in figure 3(a) for typical values of modal gain

$$P \propto \frac{e^{GL} - 1}{G}.$$  

The spectral modulation observed within the electro-luminescence (EL) spectrum of a SLD is defined [16] as $|\text{peak-valley}|/(\text{peak} + \text{valley})$. Gain can be extracted from the modulation (peak/valley ratio) in the sub-threshold EL spectrum using the Hakki–Paoli equation [17]. From the definition of the SMD and the modulation, SMD can be related to gain as:

$$\text{SMD} \propto \left( e^{-GL} + R \right)^2.$$  

By fixing the reflectivity ($R$) at $4 \times 10^{-7}$ ($R_{\text{rear}}$ is taken from the results in figure 2 and $R_{\text{front}}$ was set to $1 \times 10^{-4}$, a typical $R_{\text{eff}}$ for a tilted facet), SMD can be plotted as a function of gain for devices with three different active stripe lengths, as shown in figure 3(b). Since the power and SMD are both functions of the modal gain, from the equations (1) and (2), SMD can be plotted as a function of output power as shown in figure 3(c).

It is possible to ascertain the $R_{\text{eff}}$ of our window-like SLD structure through a study of the threshold current density, $J_{th}$, of standard Fabry–Perot lasers, as a function of increasing window length. First, construction of a plot of gain, $G$, versus current density, $J$, allows extraction of $G_c$ and $J_c$. The $G$–$J$ curve is shown in figure 2(a), with upper and lower bounds to the data providing a range of possible $G_c$ values. Our extrapolation to high current density does not take into account nonlinearity of $G$–$J$ relations such as spectral and spatial hole burning [14], since we assume these to be low in SLDs compared with lasers. Next, 1 mm long stripe waveguides with varying window section lengths (0–2.25 mm) were processed normal to the cleaved facet and $J_{th}$ was recorded for devices as a function of increasing window length, $l$, until the point at which lasing could no longer be achieved. Using these values of $J_{th}$, conversion into $G_{th}$ allows an excess loss resulting from the window, $\alpha$, to be calculated as the windowed $G_{th}$—laser $G_{th}$. $R_{\text{eff}}$ is then determined from $R_{\text{eff}}^{\text{out}}$, where $R_{\text{cl}}$ is the reflectivity of the cleaved facet. $R_{\text{eff}}$ is plotted as a function of window length in figure 2(b). We can therefore conservatively suggest that $R_{\text{eff}}$ reaches $<10^{-11}$ at a window length of 2.25 mm. Tilting the waveguide with respect to the crystal axis can be expected to reduce $R_{\text{eff}}$ further. We note that at these very small values, the reflectivity of the transition region between the stripe and window-region may dominate in producing ripple and parasitic lasing.

In order to demonstrate the relative performance of SLDs with different stripe lengths, the characteristics of SLDs with
Figure 2. (a) $G$–$J$ curve recorded from different length lasers. Upper and lower bounds are fit using $G_0 = 70\,\text{cm}^{-1}$ (dashed) and $95\,\text{cm}^{-1}$ (dotted). Effective reflectivity, $R_{\text{eff}}$, is plotted as a function of window length in (b) for $G_0 = 85\,\text{cm}^{-1}$, with error bars associated with using $G_0$ as $70\,\text{cm}^{-1}$ (upper) and $95\,\text{cm}^{-1}$ (lower).

Figure 3. (a) Simulated power, and (b) spectral modulation depth, as functions of gain for 1, 2 and 3 mm active stripe lengths. (c) Plots the corresponding SMD as a function of power.
three different geometries (1 mm with 1 mm window, 1.7 mm with 0.7 mm window and 3 mm with 2 mm window) are compared in figure 4. Comparison of SLDs with comparable stripe length (1.7 mm) but different window lengths (0.7 and 1.2 mm, not shown) revealed no measurable difference in performance, effectively decoupling the effects of stripe and window length at these long window lengths. Figure 4(a) plots the output power as a function of current density for the three SLDs. Lasing is suppressed up to the maximum powers shown.

High resolution EL spectra were recorded using an Advantest Q8384 optical spectrum analyser with 0.01 nm resolution. A mode spacing of 0.08 nm allows accurate determination of the peak and valley intensities within the spectrum. This mode spacing is consistent with the length of the active stripe, corresponding to reflection at the stripe/window interface. Figure 4(b) plots the evolution of the EL spectrum of the 1.7 mm long SLD, recorded at a lower resolution of 0.1 nm from 1 to 30 mW, for clarity. The peak emission wavelength of the 1.7 mm long SLD is plotted in the inset to figure 4(b) as a function of its output power, from 1 to 32.6 mW. At high current densities the central wavelength of the emission spectrum is observed to red-shift by \( \sim 6 \) nm away from the low current peak when \( \sim 6 \) kA cm\(^{-2} \) is injected, as a result of Joule heating in the device under continuous wave operation.

A plot of SMD as a function of output power is constructed in figure 4(c) from high resolution spectra, together with fits to the data as shown by the dotted lines. A small section of high resolution spectra, recorded at 10 mW output power, are shown in figure 4(d). The SLD is seen to increase with increasing power for all stripe lengths, with a smaller gradient for larger stripe lengths, consistent with the prediction in figure 3(c). It is possible to fit the data in figure 4(c) only at low current. However, at high current, an abrupt deviation occurs.

Absorption in the window-like region of our SLD is beneficial in attaining such low \( R_{\text{eff}} \). At low current densities (corresponding to low output powers) light travelling from the active stripe through the window region will be absorbed, contributing to the very low SMD. As observed in figure 4(b), at higher current densities self-heating in the active stripe results in a red-shift of emission. Meanwhile, non-ideal heat spreading in the buried stripe means that the unpumped window region probably operates at a cooler temperature, and the SLD emission peak shifts to the longer side of the absorption peak. The lower absorption available at these longer wavelengths may therefore permit light to travel...
through the window, which becomes increasingly transparent with increasing current density.

This mechanism can be linked to the behaviour observed in figure 4(c), in which two fits are necessary to the SMD versus power curve for the SLD with 1.7 mm stripe length, with differing rear facet $R_{eff}$—one for powers $<20$ mW and another for powers $>20$ mW, corresponding to two different values of $R_{eff}$ in the simulation. Below 20 mW the central emission wavelength is still coincident with the absorption peak in the window, while at higher powers the central wavelength is red-shifted to about 998.5 where the absorption is clearly reduced. Here, the measured SMD value is better fit by a line calculated using a larger $R_{eff}$. At the same time, the period of the highest spectral modulation is observed to change from 0.074 nm at 5 mW output power to 0.06 nm at 32.6 mW, consistent with a change in the dominant feedback cavity from reflection at the interface to reflection at the end facet for longer wavelengths $>1000$ nm. At shorter wavelengths the mode spacing remains at 0.074 nm.

Higher power SLDs have been reported, such as 1.3 W [8] but are based on measurement of broad area devices as opposed to the narrow stripe reported here. At this point in time, commercially available SLDs based on similar active widths demonstrate similar performance (power and spectral modulation) to that reported here. Our approach therefore offers comparable performance, but avoids the need for application of AR coatings, which will be beneficial in the pursuit of broader bandwidth SLDs. Alternatively, ultra-low ripple is possible via facet coating in future. Furthermore, it is anticipated that such a high level of feedback suppression could allow waveguides to be processed parallel to the crystal axis. Using such normal-facet approaches will allow a smaller chip size and improved beam quality (and hence fibre-coupling efficiency) as compared to tilted waveguides.

Conclusion

We have demonstrated a GaAs-based SLD based on a self-aligned stripe process with incorporation of a window-like back facet for attainment of low $R_{eff}$ over a broad bandwidth, without application of facet coatings. This has resulted in realisation of high power ($>30$ mW) and low SMD (<5%) SLDs. Design criteria for high power and low SMD have been discussed, with longer length SLDs offering lower SMD to higher powers.

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