Effect of saturable absorber in 1.5 µm wafer-fused vertical cavity surface-emitting lasers

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Abstract. The static characteristics of 1.5 µm wafer-fused VCSEL with the thin n++-InGaAs/p++-InGaAs/p~InAlGaAs tunnel junction (TJ) were investigated. The devices with the 8 µm diameter of the buried tunnel junction (BTJ) demonstrate effective single-mode lasing. A rapid increase in the threshold current, accompanied by an abrupt change in the output optical power is observed for devices with BTJ-diameter less than 7 µm. The observed behavior can be explained by increasing in the overlap of the optical mode with the unpumped (passive) part of the active region, which leads to the additional optical absorption. On the one hand, since the high-order transverse modes have the higher optical losses due to larger overlap with the unpumped part of the active region, then lasing via fundamental mode is more preferable even at large size of BTJ region. On the other hand, the reduction of effective index step between the BTJ region and the regions outside BTJ (caused by using small TJ etching depth) and the lateral smoothing of the difference in the height of the surface relief after TJ regrowth results in the significant drop of the transverse optical confinement factor and rise of absorption. Moreover, the absorption effect can be also strongly enhanced by increasing the heatsink temperature due to decreasing in the gain-to-cavity detuning.

Long-wavelength vertical cavity surface-emitting lasers (VCSELs) are of interest not only in terms of promising laser sources for digital and analog fiber optic communication lines and optical interconnections of silicon electronic circuits (the so-called silicon photonics), but also for creating various gas sensors [1]. In the latter case, it is a quit important to provide high-power single-mode lasing with the possibility of tuning the emission wavelength in a wide range by changing in the bias current and heat-sink temperature. A number of different approaches for fabricating these devices have been developed, involving monolithic growth of VCSEL structure and hybrid integration with dielectric distributed Bragg reflectors (DBR) or AlGaAs DBRs by wafer fusion technique. The most promising VCSEL design utilize the vertical microcavity with the carrier injection through intraicavity contact (IC) layers along with combination of tunnel junction (TJ) to minimize free-carrier absorption in doped layers (especially p-type). However, characteristics of the monolithic InAlGaAsP/InP VCSELs [2] are significantly inferior in comparison to the hybrid InAlGaAs/InP VCSELs with high-contrast dielectric
DBRs [3] and the wafer-fused InAlGaAsP/AlGaAs VCSELs [4], where the buried tunnel junction (BTJ) concept was used to achieve effective lateral current and optical confinement. Due to strong index-guiding effect only devices with the small BTJ-diameter can lase via a fundamental mode and remain single-mode operation in the wide current and temperature range. However high electrical and thermal resistance causes early output optical power saturation with the current increasing. Hence the devices with large BTJ-diameters are needed in order to increase single-mode output powers. But the maximum single-mode output power is limited by high-order modes appearing (switching to multimode operation) due to current crowding and the spatial hole burning effect, so it quickly reaches maximum and then rapidly drop with the increasing of the BTJ-diameter. During MOVPE regrowth the surface relief formed in TJ can be partially planarized by n-InP IC-layer. This leads to reduction of the index-guiding effect and allows single-mode operation for larger BTJ-diameters. In fact, the lasing via fundamental mode was demonstrated for the hybrid InAlGaAs/InP VCSEL with BTJ-diameter up to 11 μm [5] and the record high single-mode output optical power of 8 mW at 0ºC was achieved for the wafer-fused InAlGaAsP/AlGaAs VCSEL with a 7 μm BTJ-diameter [6]. Effective and reproducible use of solid-source MBE for regrowth of the TJ surface relief maintaining low internal optical losses is possible for the modified TJ design n++-InGaAs/p++-InGaAs/p++-InAlGaAs. However in case of MBE regrowth, the thickness difference caused by local etching-off the upper n++-InGaAs layer will be preserved, therefore making the issue of obtaining a single-mode operation at larger BTJ-diameter more challenging for MBE technology. The most straightforward approach to reduce index-guiding effect caused by BTJ is decreasing the TJ etching depth.

In this work, we present the experimental analysis of the static characteristics of the wafer-fused VCSELs emitting in the 1.5 μm wavelength range. We discuss the reasons of the observed nonlinearity in the light-current characteristics and the stable single-mode operation in the wide BTJ-diameter range.

**Figure 1.** Schematic cross section of a 1.5 μm range wafer-fused VCSEL. DBR, IC, TJ and BTJ denote distributed Bragg reflector, intra-cavity contact, tunnel junction and buried tunnel junction, respectively.

The 1.5 μm range wafer-fused VCSEL heterostructure consists of a GaAs substrate, a bottom GaAs/Al0.95Ga0.05As DBR, bottom fusion n-InGaAsP layer, a 2.5λ-thick InAlGaAsP optical cavity, top fusion n-InGaAsP layer and a top GaAs/Al0.9Ga0.1As DBR. The top and bottom DBRs have 20.5 and 35 mirror pairs, respectively. The InAlGaAsP optical cavity incorporates the λ-thick bottom n-InP IC-layer with average doping about 1·1018 cm⁻³, active region based on seven 2.8 nm thick In0.74Ga0.26As quantum wells (QW) with a compressive strain of 1.4%, separated by 12 nm thick lattice-matched In0.53Al0.16Ga0.31As barrier layers, 32 nm-thick n++-In0.53Ga0.47As/p++-In0.53Al0.16Ga0.31As TJ, 47 nm-thick p-InAlAs cladding with doping about 5·10¹⁷ cm⁻³ and the λ-thick top n-InP IC-layer. The top IC-layer is gradient-doped from 5·10¹⁷ cm⁻³ to 1·10¹⁹ cm⁻³ to reduce the depletion-layer capacitance of reverse biased p⁻n diode outside BTJ and minimize the electrical resistance by maintaining low optical losses. To avoid significant free-carrier absorption the TJ layers with doping up to 5·10¹⁹ cm⁻³ and two thin n-InP regions with doping up to 1·10¹⁹ cm⁻³ to form ohmic contact layers are placed at the node of the optical field, while to provide high optical confinement factors, the active region is placed at an antinode.
of the optical field. Chemical etching through the n++-InGaAs layer forms the surface relief in TJ (etching depth about 15 nm). All layers including TJ regrowth n-InP layer were grown by MBE using silicon and carbon dopants. The QW photoluminescence peak measured at room temperature is found at 1510 nm. Figure 1 shows a schematic cross section of the studied wafer-fused VCSEL structure.

Figure 2.a shows typical light-current-voltage (L-I-V) characteristics for the 1.5 µm range wafer-fused VCSEL with different size of BTJ region, measured at 20°C under continuous wave (CW) injection pumping. The devices with 8 µm BTJ-diameter have smooth light-current (L-I) curves similar to the conventional index-guided VCSELs with a reasonable gain-to-cavity detuning and threshold current of about 2mA. At the same time, the devices with smaller size of BTJ region have strong nonlinearity in the L-I-curves at bias current value above 2 mA (so called kink). Such behavior may be considered as an effective increase of threshold current. Moreover the rapid increase of the threshold current from 2 mA up to 13.6 mA was revealed with the decreasing of BTJ-diameter from 8 µm down to 4 µm. The reduction of BTJ area also result in increase of series resistance and decrease of roll-over current. The additional drop of the slope efficiency with the decreasing of BTJ- diameter also was observed probably due to self-heating effect. Note that the strong decreasing of slope efficiency for devices with small BTJ-diameter can be explained by increasing of scattering and diffraction loss caused by the refractive index discontinuity at BTJ mesa.

Figure 2. CW L-I-V characteristics (a) and emission spectra (b) at 20°C for the 1.5 µm range wafer-fused VCSELs with different size of BTJ region

Temperature stability of VCSELs under investigation is sufficiently lower as compared with the 1.5 µm range wafer-fused VCSELs with n++/p++-InAlGaAs TJ [7]. Figure 3.a shows the L-I-V characteristics for the 1.5 µm range WF-VCSEL with 8-µm BTJ-diameter measured at various heat-sink temperatures. The maximum optical output power drops linearly from 6 mW at 20°C down to 1.2 mW at 90°C, while the threshold current changes from 2 mA to up to 7.7 mA. The observed impact of temperature on VCSEL performance is more pronounced as compared to previously published results for the 1.5 µm range wafer-fused VCSEL with the active region based on the strained 2.8 nm-thick InGaAs QWs and 35 nm-thick n++/p++-InAlGaAs TJ regrown by MOCVD [7]. Note that it cannot be explained by strong difference in the internal optical losses in case of using the n++-InGaAs/p++-InGaAs/p++-InAlGaAs TJ, since the characteristics of the investigated lasers at 20°C are comparable to those of wafer-fused VCSELs with n++/p++-InAlGaAs TJ, which have a similar mirror losses and size of BTJ region. One the one hand, the poor temperature stability can be associated with the higher probability of thermal escape of the carriers from the thin InGaAs QWs due to lower height of the used In0.53Al0.16Ga0.31As barriers. One the other hand, it can be caused by smaller gain-to-cavity detuning, since the emission wavelength for VCSELs under investigation is about 20 nm less than the wavelength of the previously studied 1.5 µm range VCSEL due to slightly thinner n-InP top-IC layer [7].

Note that devices with 8-µm BTJ-diameter demonstrate only week kink effect at highest operation temperatures (see Figure 3.a). In case of devices with smaller BTJ-diameter, the appearance of L-I kink shifts to the higher currents causing the more dramatic rise of the threshold current with temperature.
As an example, the L-I-V characteristics for the 1.5 µm range wafer-fused VCSEL with 6-µm BTJ-diameter for different heat-sink temperatures is shown in Figure 3.b. The threshold current increases from 7.3 mA at 20ºC up to 13.1 mA at 60ºC resulted in vanishing of the lasing at higher temperatures.

![Figure 3. CW L-I-V characteristics for a 8-µm BTJ-diameter (a) and a 6-µm BTJ-diameter (b) 1.5 µm range wafer-fused VCSELs at various heat-sink temperatures.](image)

Generally the threshold current and slope efficiency of VCSELs are determined by the internal optical losses, mirror losses and injection efficiency. The I-V curves only have small kinks at threshold current except the large-aperture laser (where the I-V curve is smooth in whole current range). However, it can be associated with rapid change of output optical power resulted in the quick reduction of dissipated power and the laser internal temperature, while the injection efficiency is a more stable the current changing for all lasers. As for mirror loss of AlGaAs DBRs, it cannot drastically change with current/temperature due to the negligible thermal expansion of the DBR layers and the weak impact of temperature on refractive index.

Hence, one can suggest that the observed anomalous behavior is caused by drastic changes in the internal optical losses, for example, due to modification of VCSEL mode structure. In fact, each VCSEL mode has an individual internal optical loss and threshold current. Recently the anomalous behaviour of L-I curve in combination with the two-resonance modulation response has been observed in oxide-confined 850-nm range VCSELs with a large gain-to-cavity detuning [8]. The previously observed effect was explained by an anomalous start of lasing via high-order Hermite–Gaussian modes with the subsequent switching to the lowest order Hermite–Gaussian modes at higher forward bias currents, which results from the specific index guiding profile of double oxide aperture and the large gain-to-cavity detuning. However all investigated 1.5 µm range wafer-fused VCSELs exhibit single-mode emission via fundamental mode over the entire current range (see Figure 2.b) with side-mode suppression ratio (SMSR) more than 30 dB. Increasing the heatsink temperature also has no influence on the single-mode regime. It is noteworthy that the obtained single-mode operation even for large-aperture size lasers can be associated with a weaker lateral wave-guiding in case of small TJ etching depth. According to polarization-resolved studies above threshold (not presented here), the lasing emission is strongly polarized along the fixed crystallographic direction with an orthogonal-polarization-suppression ratio (OPSR) larger than 20 dB for all lasers. No polarization is revealed. Therefore, such anomalous in the L-I curves cannot be explained by the VCSEL mode competition. Besides the dramatic increase of threshold current must result in drastic reduction of slope efficiency, which does not coincide with the experimental results.

The possible reason for such anomalous behavior of L-I curves can be associated with a saturable absorption effect. The nonlinearities in the L-I-curve, accompanied by the appearance of self-pulsations, was previously observed in MBE-grown oxide-confined 980-nm range VCSELs [9]. Such a behavior was explained by optical absorption in the unpumped (passive) part of the active region located under the tapered area of the oxide aperture, which saturated at some photon density. In fact, the use of the tapered oxide aperture results in smoothing the refractive index discontinuity at oxide-semiconductor
interface and reduce the localization of the fundamental mode inside the oxide aperture (which is roughly equal to the pumped part of the active region). In case of the small-sized oxide aperture, it will increase the overlap of the optical field with the oxide aperture taper and effectively extend the unpumped part of the active region and, as a result, significantly enhance the saturable absorption effect.

Going back to our case, we can propose the similar mechanism for the creation of the unpumped part of the active region in the 1.5 µm range wafer-fused VCSEL. In the frame of the BTJ concept, the lateral structuring of the tunnel junction can provide not only effective lateral current confinement due to formation of reverse biased p'-n diode outside BTJ, but also introduce strong lateral wave-guiding (see Figure 4). Since the BTJ is located right above to the active region, the lateral current spreading can be neglected and one can assume that the size of the pumped part of the active region is equal to the size of the BTJ region. Since MBE regrowth cannot provide the planarization effect, one can easily estimate the effective index difference $\Delta n_{\text{eff}}$ between the BTJ region and the regions outside using effective index approach [10]. Very roughly the project estimated value of $\Delta n_{\text{eff}}$ is proportional to the difference in optical cavity length between the BTJ region and the regions outside. So for the proposed wafer-fused VCSEL design the effective index difference $\Delta n_{\text{eff}}$ can be estimated as about 0.01 for the TJ etching depth of 15 nm, which is still too high for single-mode operation at large BTJ-diameter. However in actual devices increasing of the size of the mesa in 1.5–2 times and lateral smoothing of the difference in the height of the surface relief after MBE-regrowth was observed by using atomic force FIB-SEM microscopy measurements. Such mesa enlargement will create the extended lateral gradient of the effective refractive index between the BTJ region and the regions outside similar to smoothing the index discontinuity by the taper of the oxide aperture in the oxide-confined VCSELs (see Figure 4).

Figure 4. SEM cross-section image of the 1.5 µm range wafer-fused VCSEL near BTJ area and the schematic transverse distributions of the effective index and optical mode HE$_{11}$. The unpumped part of the active region is highlighted in light green.

To analyze this effect the actual wafer-fused VCSEL design was approximated by the effective cylindrical waveguide with the specific index profile. Note that it is difficult to evaluate the actual profile of effective index gradient. To simplify we approximated it by two-step effective waveguide with fixed index step $\Delta n_{\text{eff-2}}$ and variable index step $\Delta n_{\text{eff-1}}$. Figure 5 shows the calculation of the transverse overlap between lateral intensity profile of the optical mode HE$_{11}$ and the pumped part of the active region (so called transverse optical confinement factor) as a function of the BTJ-diameter for the different configuration of the effective waveguide. As expected, the optical confinement factor rises with increasing of the BTJ-diameter and drops with introducing the additional index step. It means that the fundamental mode for large-aperture lasers is well confined in lateral direction within the pumped part of the active region, while the fundamental mode for small-aperture lasers deeply penetrates into the unpumped part of the active region and causes the unwanted optical absorption (see Figure 4). Under some photon concentration the unpumped part of the active region becomes transparent, i.e. this optical absorption is saturated. Moreover, the optical confinement factor falls down with decreasing of the index step $\Delta n_{\text{eff-1}}$. The weaker index-guiding resulted from the reduction of the effective index step enlarges the transverse overlap of the optical mode field with the unpumped part of the active region and, hence,
enhancing the optical absorption. It is noteworthy that the high-order transverse modes in such wafer-fused VCSEL design are mainly localized within the unpumped part of the active region and has the higher optical losses due to optical absorption, providing single-mode lasing even at large BTJ-diameter.

The behavior of the L-U-I characteristics of the lasers with the temperature changing also supports the proposed mechanism for the appearance of the nonlinearities in the L-I-curves. In fact, the gain-to-cavity detuning becomes smaller at higher temperatures due to different red-shift of gain and cavity-mode over temperature, causing the strong increase of the optical absorption at the resonance wavelength in the unpumped part of the active region and making the saturable absorption effect stronger. The more pronounced saturable absorption results in the drastic rise of the threshold current. Moreover, the mild nonlinearity in the L-I-curve at higher temperatures can be found for large-aperture lasers, which is possibly caused by the reduction of the gain-to-cavity detuning. Possibly, the adjustment of the gain-to-cavity detuning by the thickness of IC layers can lead to improvement of VCSEL performance.

Figure 5. The calculated transverse optical confinement factor versus size of BTJ region for the 1.5 µm range wafer-fused VCSEL.

In conclusion, with a decrease in the TJ thickness, the strong nonlinearity in the L-I-curves for 1.5 µm range wafer-fused VCSELs manufactured by using MBE-regrown BTJ, accompanied by the drastic increase of the threshold current and the abrupt change in the output optical power is be observed. It can be associated with the saturable absorption effect – the optical absorption in the unpumped part of the active region, which results from small effective index step (in lateral direction) between the BTJ region and the regions outside BTJ. The effect will be strongly enhanced by decreasing of the BTJ-diameter due to reduction of the transverse optical confinement factor and increasing the heatsink temperature due to the reduction of the gain-to-cavity detuning. Such effects must be taken into account during developing the designs for single-mode wafer-fused VCSEL, also for MOCVD-based VCSELs, since the saturable absorber effect can also occur in the case of using thicker TJ due to the partial planarization of the initial surface relief in tunnel junction after MOCVD-regrowth.

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