Vertical cavity surface emitting laser of 1.55 μm spectral range, manufactured by molecular beam epitaxy and wafer fusion technique

S A Bokhin¹, M A Bobrov¹, N A Maleev¹, A A Bokhin², A P Vasylyev², A G Kuzmenkov³, S I Troshkov¹, V M Ustinov², S S Rochas³, A G Gladyshev¹,³,⁴, I I Novikov⁵, L Ya Karachinsky¹,³,⁴, K O Voropaev⁵, A S Ionov⁵ and A Yu Egorov⁵

¹Ioffe Institute, St. Petersburg, 194021 Russia
²Research and Engineering Center for Submicron Heterostructures for Microelectronics, St. Petersburg, 194021 Russia
³ITMO University, St. Petersburg, 197101 Russia
⁴Connector Optics LLC, St. Petersburg, 194292 Russia
⁵OKB-Planeta PLC, Veliky Novgorod, 173004 Russia

E-mail: blokh@mail.ioffe.ru

Abstract. The heterostructure design for 1.55 μm range VCSELs is proposed and realized. The wafer fusion technique was used to form the final heterostructure. The growth of AlGaAs/GaAs distributed Bragg reflectors (DBRs) on GaAs substrate and the optical cavity with an active region on InP substrate as well as a tunnel junction (TJ) regrowth was performed by molecular beam epitaxy (MBE). A key feature of the proposed design is the use of n⁻⁻⁻⁻InGaAs/p⁺⁺⁺⁺-InGaAs/p⁻⁻⁻⁻InAlGaAs TJ, which allows, due to the effective removal of oxide from the InGaAs surface, to use MBE for re-growth of the TJ surface relief. Despite of the presence in heterostructure a narrow-gap InGaAs layers, a noticeable increase in internal optical loss in lasers can be avoided due to the short-wavelength shift of the edge of interband light absorption in n⁻⁻⁻⁻InGaAs layers (Burshtein-Moss effect). Fabricated VCSELs demonstrate single-mode operation with a threshold current less than 2 mA and a slope efficiency of ~ 0.46 W/A, which are comparable with characteristics of VCSELs with n⁻⁺⁻⁻p⁺⁺⁺⁺InAlGaAs TJ with a similar level of mirror losses.

In recent years, the noticeable interest in VCSELs emitting in the 1.55 μm wavelength range is observed due to their perspective as light sources for information and telecommunication systems. In contrast to the widely used near-infrared VCSELs based on the InAlGaAs/GaAs material system [1], creation of effective long-wavelength VCSELs based on the InAlGaAs/InP materials system, using the classical design with carrier injection through doped distributed Bragg reflectors (DBRs) is impossible due to the strong increase of free carrier absorption (especially in p-type layers). The problem could be partially solved by using of a tunnel junction (TJ) and intracavity n-type contact layers. However, monolithic heterostructure designs (grown in a single epitaxial process) with injection of carriers through n-InP/p⁺⁺⁺⁺InAlAs TJ and n-type InP intracavity contact layers are characterized by low modulation bandwidth and poor temperature stability, which is due to the use of an air aperture and low thermal conductivity DBR based on a large number of pairs of InAlGaAs/InAlAs layers, which must be
used due to the low contrast of the refractive index of DBR layers [2]. To overcome fundamental limitations of the monolithic InAlGaAsP/InP VCSEL design, the hybrid VCSEL design with carrier injection through intracavity contact layers along with combination of DBR based on other material system with simultaneously high thermal conductivity and reflectivity were proposed [3-6].

Figure 1. Schematic cross section of a 1.55 μm range WF-VCSEL. Inset: SEM image of optical cavity in the BTJ area. IC, TJ and BTJ denote intra-cavity contact, tunnel junction and buried tunnel junction, respectively.

One approach is based on wafer fusion of the optical cavity heterostructure grown on InP substrate with two AlGaAs/GaAs DBR heterostructures grown on GaAs substrates, which makes it possible to take advantage of both material systems [7]. Figure 1 shows a schematic cross section of the VCSELs design obtained by wafer fusion (hereinafter referred to as WF-VCSEL). The In(Al)GaAs quantum wells are used as the active region. Injection of carriers into the active region is realized through the intracavity contact layers of n-InP and n++/p+-In(Al)GaAs TJ. In the first works on WF-VCSEL, to ensure current confinement, small mesas in the tunnel junction were formed using local etching of the n-layer and then wafer fusion of the half-cavity heterostructure was performed directly with the heterostructure of the top DBR containing the intracavity n-GaAs contact layer [8]. This approach made it possible to block the flow of current outside the mesa due to the formation of a reverse biased p–n junction, however, the current flow through the fused GaAs-InP interface is associated with the formation of an additional potential barrier and recombination centers [9]. To overcome this situation the concept of buried tunnel junction (BTJ) was applied [5], in which the InAlGaAsP optical cavity is formed in three stages. At the first stage, the growth of the InAlGaAsP half-cavity heterostructure containing the bottom intracavity n-InP contact layer, the active region and the tunnel junction was performed. At the second stage, the mesa structures are formed in TJ layers by etching of the n++/p+-layers down to the p−-layers. At the final stage, after the procedure of oxide removing from the etched TJ surface, the top intracavity contact layer of n-InP is grown. Moreover, in most works, the metalorganic chemical vapor deposition (MOCVD) method is used to regrow the tunnel junction, since in MBE technology it is practically impossible to efficiently remove the natural oxide from the InAlGaAs surface without using in-situ surface cleaning systems. In this regard, the actual task is to develop a design of long-wavelength VCSEL, which will be suitable for using MBE for TJ regrowth without a significant changing the level of internal optical loss in VCSEL heterostructure.

Due to the high chemical activity of Al-containing layers, it is impossible to ensure the removal of natural oxide from the InAlGaAs surface even using surface cleaning pretreatment, because any exposure of the sample under atmosphere leads to the rapid formation of a new oxide layer. In this case, the procedure of thermal annealing of the samples in the MBE chamber at standard temperatures does not provide effective oxide removal from the InAlGaAs surface. As a result, the two-dimensional regrowth of the InAlGaAsP half-cavity heterostructure by the top intracavity n-InP contact layer is not possible within the classical solid-source MBE method (see figure 2.a) without the use of in-situ wafer surface cleaning systems. At the same time, for InGaAs layers, the combination of chemical surface cleaning in the HCl:H2O etchant and annealing in the MBE chamber in the temperature range 520-530°C makes it possible to efficiently remove oxide from the surface and ensure two-dimensional growth of
the n-InP layer with a low surface roughness (typical standard deviation surface roughness heights $R_s<1$ nm) and without increasing defect density, as shown in figure 2b.

**Figure 2.** SEM images of InAlGaAs (a) and InGaAs (b) surfaces after MBE-regrown by 100nm-thick InP layer.

The contact resistance of classical n$^+/p^{++}$-InGaAs TJ based on the highly doped n$^+$-InGaAs and p$^{++}$-InGaAs layers with $\delta$-doping can be reduced to the level of $3\cdot 10^{-6}$ Ohm·cm$^2$ [10]. The n$^+/p^{++}$-InGaAs TJ was successfully tested for the 1.55 μm range WF-VCSEL with the intracavity n-InP and p-GaAs contacts [4], but the key disadvantage of this design was a high internal losses due to absorption in narrow-gap InGaAs that results in relatively high threshold currents and low slope efficiency. At the same time, it is known that fundamental bandgap absorption in highly n-doped InGaAs is reduced due to a large short-wavelength shift of the edge of interband light absorption (Burshtein-Moss effect), while a huge optical absorption near the wavelength of 1.55 μm occurs in the p-doped InGaAs. Therefore, as a solution of the problem, it was proposed to replace the p$^{++}$-InGaAs layer by the p$^{++}$-InGaAs layer with a bandgap energy about 0.83 eV to reduce optical absorption and maintain small bandgap energies for efficient tunneling and low contact resistance [11]. The n$^+$-InGaAs/p$^{++}$-InAlGaAs TJ was successfully tested in the hybrid 1.55 μm range VCSEL designs with injection of carriers through intracavity contact layers in combination with high-contrast dielectric DBRs [6, 12]. To further reducing of internal losses associated with absorption in the layers of the tunnel junction, replacement of the n$^+$-InGaAs layer by an optically transparent n$^+$-InAlGaAs layer was proposed. Such n$^+/p^{++}$-InAlGaAs TJs were successfully tested for the 1.55 μm range WF-VCSEL with injection of carriers through intracavity contact layers [13-14]. In this case, MOCVD technology was used to regrow the surface relief formed by etching the mesa structure on tunnel junction.

Effective use of MBE for regrowth of the mesa structure within a tunnel junction while maintaining low optical loss is possible using the modified TJ design (n$^{++}$-InGaAs/p$^{++}$-InGaAs/p$^{++}$-InAlGaAs). The formation of mesa structure in such TJ is carried out by etching of the n$^{++}$-InGaAs layer down to the thin p$^{++}$-InGaAs layer, which prevents the surface oxidation of Al-containing layers. In this case, it is possible to avoid a noticeable increase in absorption losses due to the small thickness of the p$^{++}$-InGaAs layer and due to the Burshtein-Moss effect for the heavily doped n$^{++}$-InGaAs layer. The results of experimental approbation of the proposed n$^{++}$-InGaAs/p$^{++}$-InGaAs/p$^{++}$-InAlGaAs TJ design and its comparison with the n$^{++}/p^{++}$-InAlGaAs TJ concept are given below.

The basic design of the studied WF-VCSEL emitting in the 1.55 μm spectral range is a vertical microcavity with undoped mirrors. Injection of carriers goes through n-type intracavity contact layers and current confinement based on BTJ concept. The heterostructure consists of a GaAs substrate, a bottom DBR based on 35 GaAs/Al$\text{In}_{0.5}\text{Ga}_{0.5}$As pairs, an InAlGaAsP optical cavity with a total thickness of 2.5λ, and a top DBR based on 20.5 GaAs/Al$\text{In}_{0.5}\text{Ga}_{0.1}$As pairs. The InAlGaAsP optical cavity includes the bottom fusion n-InGaAsP layer, the $\lambda$-thick bottom intra-cavity n-InP contact layer with the highly-doped n-InGaAsP contact, the active region based on strained In(Al)GaAs QWs, the n$^{++}/p^{++}$-InGa(Al)As BTJ, p-InAlAs cladding, the $\lambda$-thick top intra-cavity n-InP contact layer with the highly-doped n-InGaAsP contact acting also as the top fusion layer. Thin highly strained In$_{0.7}$Ga$_{0.3}$As QWs (a
lattice-mismatch parameter of ~ 1.4%) separated by lattice-matched In\textsubscript{0.53}Al\textsubscript{0.16}Ga\textsubscript{0.31}As barrier layers are used as the active region. The scanning electron microscopy (SEM) image of the double-fused VCSEL heterostructure is shown in the inset of figure 1. The initial half-cavity heterostructures and DBR heterostructures were grown by MBE. For regrowth by MOCVD and MBE methods the two types of TJs – 35 nm-thick n++/p++-In\textsubscript{0.53}Al\textsubscript{0.2}Ga\textsubscript{0.27}As and 32 nm-thick n++-In\textsubscript{0.53}Ga\textsubscript{0.47}As/p++-In\textsubscript{0.53}Al\textsubscript{0.16}Ga\textsubscript{0.31}As were used respectively. Figure 3 shows the longitudinal distribution of the electromagnetic field of standing optical wave, refractive index and doping profiles of the 1.55 μm range WF-VCSEL. The active region is located at the maximum of the electromagnetic field of the optical mode, while the tunnel junction, heavily doped contact layers, and fused interfaces at its minimum. It should be noted that after fusion the quarter-wavelength GaAs layer from top DBR adjacent to the top intra-cavity contact layer, and the quarter-wavelength GaAs layer from bottom DBR adjacent to the bottom intra-cavity contact layer, effectively increase the vertical optical cavity length up to 3λ.

![Figure 3](image)

**Figure 3.** The distribution of the electromagnetic field intensity along the profile of the refractive index and doping profiles of 1.55 μm range WF-VCSEL.

To study the internal optical losses, a series of VCSEL samples based on the n++/p++-InAlGaAs TJ with various mirror losses were fabricated. Figure 4a shows the calculated dependence of the mirror losses depending on the calculated reflectivity of the VCSEL top mirror. The variation of the mirror losses was carried out by precision etching of the surface of the top DBR to a depth of 70 nm (corresponding to maximum slope efficiency), and then by local deposition of low-Q dielectric SiO\textsubscript{2}/Ta\textsubscript{2}O\textsubscript{5} DBR with a different number of pairs. The results of the analysis of internal optical losses and current injection efficiency of 1.55 μm range WF-VCSEL with the n++/p++-InAlGaAs TJ, measured at 20°C are shown in figure 4.b. Due to the use of n++/p++-InAlGaAs TJ and the optimization of the structure doping profile, it was possible to ensure the internal optical loss as low as ~6.5 cm\textsuperscript{-1} keeping the current injection efficiency more than 90% [15]. It should be noted that the level of internal optical losses achieved for VCSELs with the n++/p++-InAlGaAs TJ is 30–40% lower than the published values as for the 1.55 μm range VCSELs with a similar design obtained by fusion of MOCVD-grown optical cavity and DBR wafers [13], and for the hybrid 1.55 μm range VCSEL design with a short cavity, n+-InGaAs/p+-InAlGaAs TJ and high-contrast dielectric mirrors [12].
Figure 4. The calculated dependence of the mirror losses on top mirror reflectivity (a) and the inverse quantum efficiency measured at 20ºС versus the inverse calculated mirror losses (b) for 1.55 μm-range WF-VCSEL with the n++/p+-InAlGaAs TJ.

Figure 5 shows comparison of the current and voltage characteristics of the 1.55 μm-range WF-VCSEL with different tunnel junction designs, measured in CW mode at a temperature of 20ºC. Due to the low internal optical loss the 1.55 μm range WF-VCSELs based on the n++/p+-InAlGaAs TJ with a 7 μm BTJ-diameter demonstrate efficient lasing through the fundamental mode (single mode emission) with a threshold current less than 1.5 mA and slope efficiency of ~0.48 W/A. The 1.55 μm range WF-VCSELs based on the n++-InGaAs/p+-InGaAs/p+-InAlGaAs TJ with a 8 μm BTJ-diameter and a similar level of mirror losses demonstrate single-mode lasing with a threshold less than 2 mA and slope efficiency of ~0.46 W/A. Taking into account the identical design of the DBRs and the optical cavity for the two types of the studied VCSELs, we can make an estimation of the internal optical losses for the 1.55 μm range WF-VCSELs based on the n++-InGaAs/p+-InGaAs/p+-InAlGaAs TJ as low as 10 cm⁻¹. Thus, due to the Burshtein-Moss effect in the highly doped n++-InGaAs layer and the small p+-InGaAs layer thickness, it was possible to avoid a significant increase of internal optical loss when using the n++-InGaAs/p+-InGaAs/p+-InAlGaAs TJ, allowing the use of MBE for mesa structure regrowth.

In conclusion, the proposed design of TJ based on the n++-InGaAs/p+-InGaAs/p+-InAlGaAs layers allows to manufacture heterostructures for 1.55 μm range WF-VCSELs using the solid-source MBE including regrowth the TJ mesa structure. In the case of using the n++-InGaAs/p+-InGaAs/p+-InAlGaAs TJ, a noticeable increase in the internal optical losses compared to the n++/p+-InAlGaAs TJ design was not obtained. The manufactured long-wavelength VCSELs with two types of TJs and the same level of mirror losses demonstrate almost similar static characteristics.

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Figure 5. Room temperature light-voltage-current characteristics of 1.55 μm range WF-VCSEL with the n+/p++-InAlGaAs TJ (a) and n++-InGaAs/p++-InGaAs/p++-InAlGaAs TJ (b).

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