Minimum temperature sensitivity of 1.55 μm vertical-cavity lasers at -30 nm gain offset

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Double-fused vertical-cavity surface-emitting lasers (VCSELs) have demonstrated the highest temperature performance of any 1.5 μm VCSEL, but further optimization is needed to reduce their temperature sensitivity. We present and analyze threshold current measurements of these devices between -90 °C and 30 °C stage temperature. Despite a zero gain peak offset from the emission wavelength at room temperature, the pulsed threshold current has its minimum near -50 °C corresponding to about -30 nm gain offset. This is in contrast to a common VCSEL design rule. Temperature effects on the optical gain of the strain-compensated InGaAsP/InP active region are found to be the main cause for the disagreement. A design rule modification is proposed. Numerical simulation of an optimized 1.55 μm VCSEL shows that gain offset improvements are counteracted by loss mechanisms. © *1998 American Institute of Physics.* [S0003-6951(98)01915-9]

Vertical-cavity surface-emitting lasers (VCSELs) are attractive new light sources for various optoelectronic applications.[1] VCSEL operation is strongly temperature sensitive at long emission wavelengths (1.3 or 1.55 μm). Room-temperature continuous wave (cw) operation of 1.55 μm VCSELs was first achieved in 1995[2] and the maximum cw lasing temperature today is 64 °C.[3] These most successful 1.55 μm VCSELs employ strain-compensated multi-quantum well (MQW) InGaAsP/InP active regions which are sandwiched between wafer-fused GaAs/AlGaAs distributed Bragg reflectors (DBRs) to form the vertical cavity (Fig. 1). The emission wavelength λ_{cav} is given by the optical cavity length and its careful adjustment to the wavelength λ_{gain} of maximum MQW gain is required for lasing. The gain offset $\lambda_{gain}-\lambda_{cav}$ depends on the temperature T since λ_{cav} shifts with changing refractive index and λ_{gain} shifts with changing MQW band gap $E_g(T)$. The adjustment of the gain offset is a critical VCSEL design issue to reduce temperature effects on the threshold current I_{th}.[4] Minimum temperature sensitivity ($dI_{th}/dT=0$) is obtained at the minimum of the threshold current temperature characteristic $I_{th}(T)$. GaAs based VCSELs emitting below 1 μm wavelength show a minimum of $I_{th}(T)$ near zero gain offset.[5,6] In contrast, 1.55 μm VCSELs grown on an InP substrate exhibit the minimum threshold current far below the temperature of zero gain offset.[7,8]

This letter presents and analyzes low-temperature measurements on wafer-fused 1.55 μm VCSELs. The devices investigated are the 1.55 μm VCSELs which exhibited first room-temperature cw operation.[2,9] The laser structure is shown in Fig. 1. The active region consists of seven 5.5 nm $In_{0.76}Ga_{0.24}As_{0.82}P_{0.18}$ quantum wells at about 1% compressive strain and six 8 nm $In_{0.48}Ga_{0.52}As_{0.82}P_{0.18}$ barriers at about 0.8% tensile strain. This MQW is embedded in 300 nm thick InP spacer layers that are fused to a 28-period n-doped GaAs/AlAs DBR on the bottom and to a 30-period p-doped GaAs/AlGaAs DBR on the top (pillar). Light is emitted through the GaAs substrate at 1542 nm wavelength ($T=20$ °C). The emission wavelength shift with temperature is $d\lambda_{cav}/dT=0.11$ nm/K in pulsed operation. These devices were designed for room temperature lasing with a MQW photoluminescence (PL) peak at 1535 nm, measured at 20 °C before fusion. The PL peak wavelength shift with temperature was measured on similar MQWs[8] to be $d\lambda_{PL}/dT=0.54$ nm/K giving a thermal band-gap shrinkage of $dE_g/dT=-0.28$ meV/K which is about two thirds of typical GaAs values.[10] The PL peak is only a few nanometers blue-shifted from the gain peak. Thus, zero gain offset ($\lambda_{gain}-\lambda_{cav}=0$) is expected near room temperature. It is a common VCSEL design rule, that the threshold current $I_{th}(T)$ has its minimum at zero gain offset.[5,6] However, such a minimum was not observed in our previous pulsed measurements at $T>0$ °C.[11] For this reason, we now use a cryo-

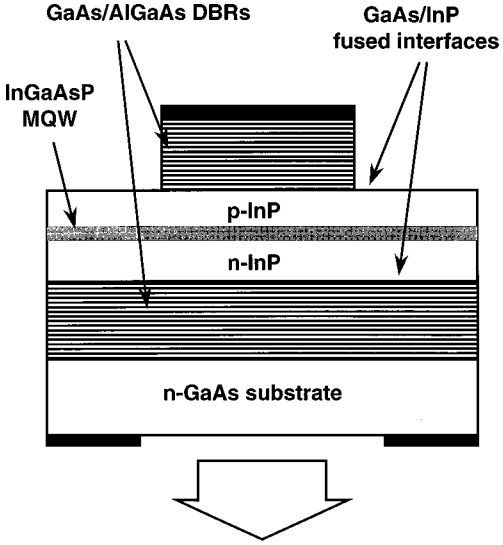

FIG. 1. Double-fused 1.55 μm vertical-cavity laser.

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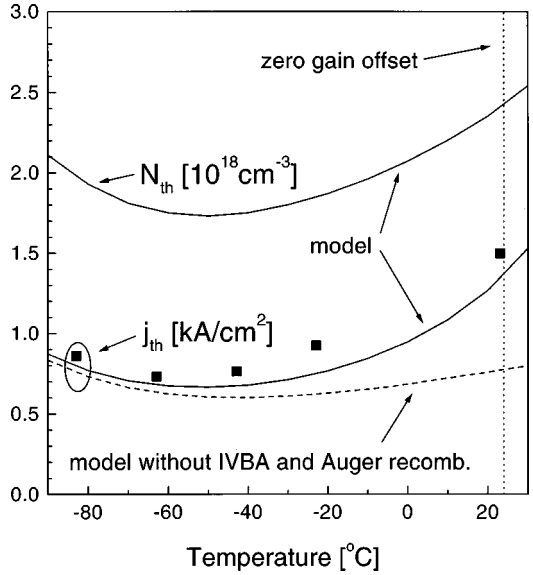

FIG. 2. Threshold current density j_{th} and threshold carrier density N_{th} vs stage temperature T in pulsed operation (dots: measurement, solid lines: simulation, dashed line: j_{th} simulation excluding IVBA and Auger recombination).

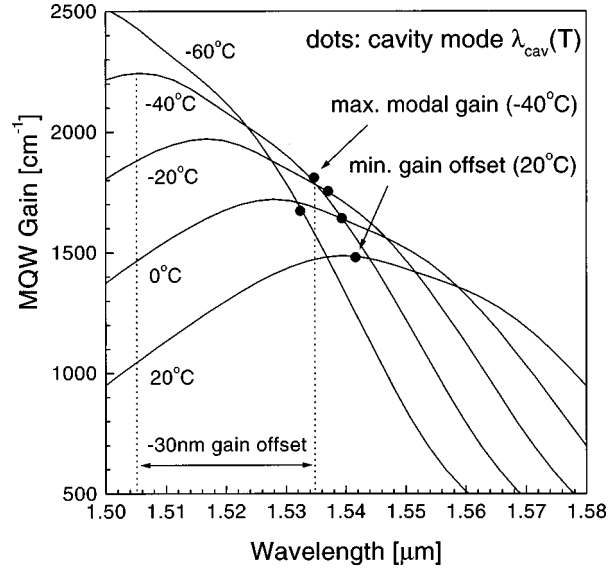

FIG. 3. MQW gain spectra $g(\lambda)$ at constant carrier density for different temperatures T. The dots give the emission wavelength $\lambda_{cav}(T)$ and the actual gain of the cavity mode.

genic vacuum chamber to perform measurements at low temperatures to find the minimum of the threshold current. Pulsed operation with less than 1% duty cycle is used to maintain a uniform internal VCSEL temperature equal to the stage temperature. The experimental results are shown in Fig. 2 (dots) for a device with 20 μm pillar diameter. The lowest threshold current is measured at -60 °C, i.e., at considerable negative gain offset. Multiple probing of the small DBR pillars often causes device degradation, so only a few data points are taken.

We analyze our measurement using a comprehensive two-dimensional VCSEL model.[11] This model has shown excellent agreement with a variety of measurements on double-fused VCSELs at $T>0$ °C. The MQW band structure is determined using a 4×4 $\mathbf{k}\cdot\mathbf{p}$ model.[12] Gain calculations are based on Fermi's Golden Rule including many body effects.[13,14] The transmission matrix method[15] is employed for optical simulation including temperature effects on layer thickness, absorption, and refractive index. Carrier transport is simulated using a two-dimensional finite-element code including spreading current and carrier leakage from the MQW. Material parameters and their temperature dependencies have been adjusted carefully to fit previous measurements.[11] The same parameters are used now to simulate laser performance at low temperatures. The calculated threshold current density $j_{th}(T)$ agrees very well with our experimental data (lower solid curve in Fig. 2). It shows a minimum at -50 °C, the same temperature at which the calculated threshold carrier density $N_{th}(T)$ is lowest (upper solid curve in Fig. 2). In previous investigations, intervalence band absorption (IVBA) and Auger recombination have been identified as the most temperature sensitive loss mechanisms in our 1.55 μm VCSELs.[11,16] Both IVBA and Auger recombination rise with higher temperature *and* with higher carrier density. Exclusion of those two loss mechanisms from the model gives the dashed curve in Fig. 2. As result of this exclusion, the position of the $j_{th}(T)$ minimum is shifted only slightly to -40 °C, indicating that the minimum in the threshold current is a gain related effect. Zero gain offset is calculated at 24 °C.

Based on the good agreement of our model with all experimental data, temperature effects on the calculated gain are now evaluated in detail. We will show that the optical cavity mode *does not* receive maximum gain at zero gain offset, as commonly assumed. The MQW material gain $g(\lambda,N,T)$ is a function of wavelength λ, carrier density N, and temperature. The effect of the temperature on the MQW gain spectrum $g(\lambda)$ is shown in Fig. 3 for constant carrier density. The dots in Fig. 3 indicate the VCSEL emission wavelength $\lambda_{cav}(T)$ and they give the actual modal gain at each temperature. At 20 °C, the gain peak wavelength $\lambda_{gain}=1540$ nm is only 2 nm smaller than the emission wavelength λ_{cav}. As the temperature is reduced, the gain peak is not only blueshifted, the maximum of the gain spectrum also increases strongly. This increase $dg_{max}/dT=-10\ \mathrm{cm}^{-1}\ \mathrm{K}^{-1}$ is attributed to the decreased Fermi spreading of carriers in the quantum wells. It is about double the number measured on GaAs lasers[17] due to differences in the density of states. The maximum modal gain is reached at -40 °C corresponding to -30 nm gain offset. Without loss effects and with almost constant threshold gain, this maximum modal gain results in minimum threshold current at the same temperature (dashed curve in Fig. 2). Thus, the modeling clearly shows that about -30 nm gain offset is necessary in our 1.55 μm VCSELs to obtain minimum temperature sensitivity of the threshold current. Similar temperature effects occur in GaAs VCSELs but the optimum gain offset is much closer to zero.

Most VCSEL applications require low temperature sensitivity at or above room temperature, i.e., our $I_{th}(T)$ minimum should be moved to higher temperatures. In order to achieve this at constant emission wavelength, the gain spectrum needs to be blueshifted by raising the MQW band gap. This optimization method is known from GaAs VCSELs[4,6] as well as from distributed-feedback edge-emitting lasers.[18] In

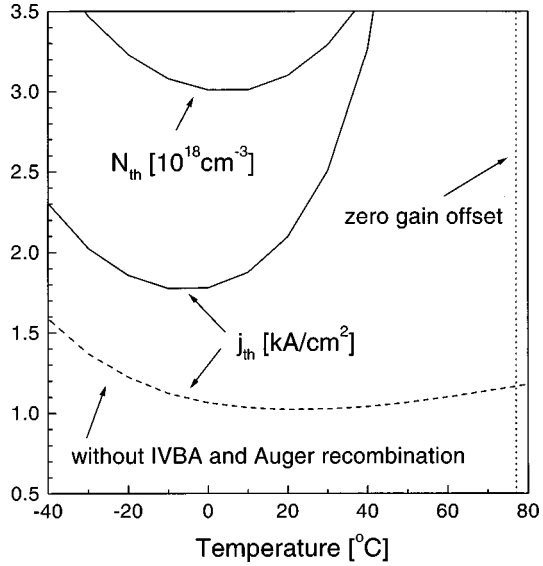

FIG. 4. Simulation results as in Fig. 2 with 26 nm blueshifted gain spectrum.

our 1.55 μm VCSELs, the present gain offset at 20 °C is $\lambda_{gain}-\lambda_{cav}=-2$ nm (Fig. 3). To obtain -30 nm gain offset ($dI_{th}/dT=0$) at that temperature, the gain spectrum has to be blueshifted by 28 nm. To simulate such a device optimization, we reduce the quantum well thickness in our model. Nine 4.2 nm quantum wells and eight 6.0 nm barriers are assumed, maintaining strain compensation and keeping the total thickness of the active region almost constant. The band-gap wavelength of this new MQW is 26 nm smaller than in the original structure. With this optimized MQW, the simulation results of Fig. 2 are recalculated and shown in Fig. 4 (notice the shifted graph window). Without IVBA and Auger recombination the lowest threshold current now occurs near 20 °C, as expected (dashed curve). Inclusion of those losses gives a minimum at -10 °C (solid curves). The threshold current density $j_{th}(T)$ is higher than in the original device. The reason for that is the larger threshold carrier density N_{th} which is mainly due to the lower gain. Larger carrier densities cause higher IVBA losses which also contribute to the N_{th} increase. Thus, the intended optimization of our device is counteracted by loss mechanisms. The simulation results do not suggest an increase of the MQW band gap in our present 1.55 μm VCSELs since low threshold current is of paramount importance to reduce device heating in cw operation above room temperature. However, after further reduction of the threshold current in future devices, gain offset adjustment is recommended to obtain minimum temperature sensitivity above room temperature.

In conclusion, the modification of a VCSEL design rule is proposed as follows. To obtain minimum temperature sensitivity of the threshold current, negative offset of the gain peak from the emission wavelength is required. This gain offset is near zero in the case of GaAs VCSELs emitting below 1 μm, whereas it is about -30 nm in the case of our 1.55 μm InP VCSELs. In other words, the optimum gain offset depends on the active region material. However, loss mechanisms can have a strong influence on the temperature at which minimum temperature sensitivity is obtained.

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