Threshold current reduction due to piezoelectric effects in InGaAs/AlGaAs laser diodes

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Abstract. We show that despite expectations the piezoelectric field present, for instance, in strained InGaAs quantum wells (QWs) grown along the (111)B orientation, can lead to a significant threshold current reduction in laser diodes (LDs) using piezoelectric QWs as active medium. We have fabricated a series of LD structures in variable cavity lengths, with a single 10nm-thick InGaAs/AlGaAs active QW, grown either on (100) or (111)B GaAs substrates. We have observed for all temperatures in the range 20-300K, and for all cavity lengths between 0.5-2mm, systematically lower threshold currents in the (111)B LDs compared to their (100) counterparts. To interpret this unexpected result, we have employed modeling of the devices based on a self-consistent Schroedinger-Poisson solver, incorporating strain and screening effects, as well as the piezoelectric field dependence of gain and spontaneous emission rate.

1. Introduction
Strained QWs, grown on substrates oriented along a polar axis, have recently gained attention due to the extra degree of engineering freedom they provide. Novel devices such as electro-absorption modulators were the first to benefit from this approach [1-3]. Recently, laser diodes (LDs) with strained active QWs grown along (111) B orientation, have shown comparable [4] or even improved [5] performance compared to their conventional, non-polar, counterparts. Even though such improvement should be related to the unique physics involved in these devices, namely, the piezoelectric effects as well as the increased hole effective mass [6,7], still to this date the exact role of the piezoelectric field in the lasing characteristics of piezoelectric QWs remains unclear.

In order to shed light on this issue, we have grown a set of identical laser structures on (100) and (111) B GaAs substrates. The LDs obtained, were characterized by optical power output versus injection current measurements. The experimental results were compared to theoretical calculations of gain in strained piezoelectric QWs. This analysis explains the observed threshold current and gain characteristics enhancement and provides useful insight for designing novel devices, which take advantage of piezoelectric fields.

2. Results and Discussion
For this study, two identical separate confinement heterostructure single quantum well laser structures were grown on (100) and on (111) B oriented GaAs 2-inch substrates. A 10nm thick In₀.₁Ga₀.₉As layer sandwiched between two, 125nm thick, Al₀.₁₅Ga₀.₸₅As layers formed the QW. P-type (Ti/Pt) contacts were deposited on top by e-beam evaporation. Ridges, 2.3µm high, were formed by wet chemical etching in order to provide optical and electrical confinement. Wafers were thinned down to 150µm by chemo-mechanical polishing. Subsequently, n-type (Au/Ge) contacts were deposited on the wafers’
back side. The ridge width was systematically varied from 10µm to 50µm. Cleaving was employed to form the laser cavities with lengths ranging from 500µm to 2mm. Laser mirrors were uncoated and their reflectivity $R$ was estimated to be approximately 32%.

The LDs were mounted on ceramic holders and were electrically excited using square current pulses (500nsec wide), at a repetition rate of 10KHz (duty cycle 0.5%) to avoid heating effects. A high numerical aperture collection lens was used to couple all the power output from one mirror to an optical power meter. The optical emission spectra were recorded using a spectrograph equipped with a LN$_2$-cooled CCD.

In figure 1, the threshold current densities $J_{th}$ measured at T=20K on a number of (100) and (111) B devices are plotted as a function of inverse cavity length $L^{-1}$. As observed in the data, the $J_{th}$ of (100) oriented LDs is considerably larger in comparison to the corresponding (111) B LDs. This holds true for all cavity lengths employed.

![Figure 1](image-url)

**Figure 1.** Threshold current density measured at low temperature (20K) for different cavity lengths. The improved performance of (111) B grown devices is evident from the systematically lower threshold of operation.

In order to correlate our experimental results to theoretical $J_{th}$ estimates, it is important to estimate the internal losses in our laser structures. This is accomplished by measurements of the total optical output power above threshold as a function of injection current. This allows the determination of $J_{th}$, as well as the slope efficiency ($\Delta P/\Delta I$), for each device. Subsequently, the differential quantum efficiency $n_d$ is calculated according to the relation $n_d = \left(1/hv\right) \left(\Delta P/\Delta I\right)$, where $hv$ is the energy of the emitted photons. The differential quantum efficiency $n_d$ is related to the internal quantum efficiency $n_i$ and the value of internal cavity losses $a_i$ by the following equation:

$$\frac{1}{n_d} = \frac{1}{n_i} + \frac{1}{n_i} \cdot \frac{a_i}{\ln\left(\frac{1}{R}\right)} \cdot L$$

(1)

where the same reflectivity $R=32\%$ is assumed for both mirrors. Therefore, the dependence of measured $n_d$ on cavity length $L$ allows, using equation1, the extraction of the values of both $n_i$ and $a_i$. The value of $a_i$ for (111) B and (100) oriented laser structures was found to be 13cm$^{-1}$ and 7cm$^{-1}$, respectively. The threshold gain in a given laser cavity is given by the following equation

$$\Gamma g_{th} = a_i + \frac{1}{L} \ln\left(\frac{1}{R}\right)$$

(2)

where $\Gamma$ is the optical confinement factor in the active layer. For the structure under investigation, the optical confinement factor has been calculated equal to 2.32%. Given the value of $a_i$ for each
orientation, the \( g_{th} \) of the laser devices characterized, was estimated to be in the range of 800-1550 cm\(^{-1}\) and 500-1300 cm\(^{-1}\) for (111)B and (100) oriented devices, respectively. Thus, a higher threshold gain is necessary for lasing operation in the devices grown on (111) B oriented substrates due to higher losses. Despite that, a lower threshold current density is observed in these devices for all cases of cavity lengths.

Theoretical calculation of the threshold current density, to obtain a given gain in the structure under investigation, was employed in order to account for this unexpected result. The model is based on a Schroedinger-Poisson self-consistent solver, described in detail elsewhere [5,8]. Based on the above mentioned algorithm, it is possible to extract gain spectra for any given temperature and carrier density in the active QW. It is important to note that the carrier-induced modification of the band profile is inherently included in this model. Band profile modification in piezoelectric QWs is necessary in order to include screening effects which are significant due to the field-induced spatial separation of the injected carriers. A given carrier density is thus mapped to a gain curve and a corresponding gain maximum. The gain spectrum whose maximum matches a given value of \( g_{th} \) is selected and the corresponding spontaneous emission rate is calculated. Given that all non radiative and leakage processes, are neglected, the threshold current \( J_{th} \) is essentially the one needed to sustain the resulting spontaneous emission [8]. Following the described process, estimates of \( J_{th} \) as a function of \( g_{th} \) are computed.

The calculated \( J_{th} \) versus \( g_{th} \) curves (solid curves) are plotted in figure 2. It is observed, from the data plotted, that for all \( g_{th} \) values, the \( J_{th} \) is considerably lower in the (111) B case. One of the main reasons for this reduction is the lighter in-plane heavy-hole mass in the (111) B case. This is depicted by the dashed curve that corresponds to the calculation using (111) B parameters, without including the piezoelectric field in the QW. In this case, the reduced \( J_{th} \) is a consequence of the modified density of states especially in the heavy hole states, resulting in sparser electronic states and hence easier population inversion. It should be noted that the experimental curves of figure 1 converge with increasing inverse cavity lengths (i.e. high cavity losses). On the contrary, the theoretically calculated, zero-field, dashed curve in Figure 2 diverges from the (100) curve for high \( g_{th} \).

![Figure 2. Theoretically calculated threshold current density for 20K, with varying gain necessary to start laser operation, for the (100) and (111) laser structures described in the text.](image-url)

Comparison of the calculated (111) B curves with and without including the piezoelectric field, leads to the following observation. In the low \( g_{th} \) regime, the piezoelectric field has a positive effect. On the other hand, above a certain \( g_{th} \) regime, the piezoelectric field has a negative effect. In a piezoelectric QW there is a significant spatial separation between electron and hole wavefunctions. The main effect is a reduced overlap between electron and hole
wavefunctions in the QW. Thus, a reduced recombination probability between electron and holes present in the QW. With increasing carrier density, the piezoelectric field is partially screened by the carriers in the QW. However, as shown by our calculations, there is a significant residual field inside the QW even at carrier densities high enough to obtain lasing. This has been also observed experimentally [9]. For a given carrier density, this implies a reduced gain. In other words, threshold gain is achieved at higher carrier density in the piezoelectric QW. On the other hand, spontaneous emission is reduced as well. As a consequence, fewer carriers recombine spontaneously. To a good approximation, the main mechanism - below threshold - for carrier annihilation is spontaneous emission. This leads to the conclusion that the interplay between the two mechanisms described above decide whether the piezoelectric field would have a positive or a negative effect. In the low-gain region of Figure 3, the spontaneous emission reduction is dominant leading to a positive effect. However, at increased gain level, reduction of the spontaneous emission is not enough to counteract the negative effect. Thus the overall performance deteriorates.

As described thus far, the effective mass difference between the two systems under investigation, may explain the difference in threshold. However, the slope difference observed in Figure 1 between (100) and (111) B oriented devices, is not predicted by the effective mass difference alone. On the contrary taking into account the piezoelectric effects, consistency between theoretical and experimental data is improved. This is a strong indication that indeed the described model is indeed applicable in the investigated system.

3. Conclusions

(111) B oriented laser diode structures have been shown to present an attractive reduced-threshold alternative to (100) oriented devices. The underlying mechanism has been isolated and modeled utilizing a Schroedinger-Poisson quasi-static model. Namely, not only reduced density of states but reduced spontaneous emission rate is identified as the mechanism of the further reduction of the lasing threshold. The implications are important both for the technologically mature arsenide-based material systems, as well as for nitride semiconductors. Nitrides exhibit one order of magnitude larger internal fields. Thus, excellent understanding of the piezoelectric field implications is necessary to handle nitride based laser diodes.

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5. References

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