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Full Length Research Paper

Number of p-type distributed Bragg reflectors effects on gallium nitride (GaN)-based vertical cavity surface emitting laser performance

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This paper has presented the characteristic features of the reflectivity of the output mirror at 415 nm vertical cavity surface emitting lasers with various distributed Bragg reflectors pairs. For this, vertical cavity surface emitting lasers with various corresponding p-distributed Bragg reflectors pairs are simulated using integrated system engineering simulation program. The output power and the threshold current for each of these devices were determined. We found that by increasing distributed Bragg reflectors pairs, the distributed Bragg reflectors reflectivity increased, which can reduce the device lasing threshold. However, the external differential quantum efficiency was inversely related to top mirror reflectivity. So, the optical output of the device also decreased with increased p-type mirror pairs. A suitable distributed Bragg reflectors design is carefully selected for the pair number so as to balance among low lasing threshold current, high output power, and high efficiency.

Key words: Semiconductor lasers, vertical cavity surface emitting laser, distributed Bragg reflectors, external quantum efficiency, multiple quantum well.

INTRODUCTION

The vertical cavity surface emitting laser (VCSEL) consists several quantum wells in the center of device and two spacer layers forming a separate confinement for efficient carrier trapping and optical confinement. Gallium nitride (GaN)-based is great interest for short wavelength optoelectronics and microwave power devices (Rezaee Rokn-Abadi, 2010). Nitride-based vertical cavity surface emitting lasers have various advantages such as great potential for two dimensional short-wavelength laser arrays. The possibility of high density and high speed optical data storage are provided by this property of GaN-based VCSEL (Arita et al., 2002). The laser cavity length of a VCSEL is very short, typically 1 to 2 wavelength of the emitted light. A photon has a small chance to triggering a simulated emission event at low carrier densities as a result, in a single pass of the cavity (Chow et al., 1997). For low threshold current, the VCSELs require highly reflective mirrors with reflectivity greater than 99% (Pramanik et al., 2011). Since the high reflectivity cannot be achieved with metallic mirrors, therefore, semiconductor multilayered mirrors with high reflectivity and low absorption loss, which is called distributed Bragg reflectors (DBRs) can be provided (Pramanik et al., 2011). DBRs consist of epitaxially grown of repeating pairs of quarter-wavelength-thick high and low refractive index semiconductor layers (Jasim et al., 2010). Combining the multiple quarter-wavelengths thick high-to-low refractive index layers will result to maximum reflectance greater than 99% (Al-Omari and Lear, 2004). The reflectivity of single DBR at normal incidence can be calculated using the following simple equation (Jasim et al., 2010):

where n is the number of the DBR pairs, n_L and n_H are

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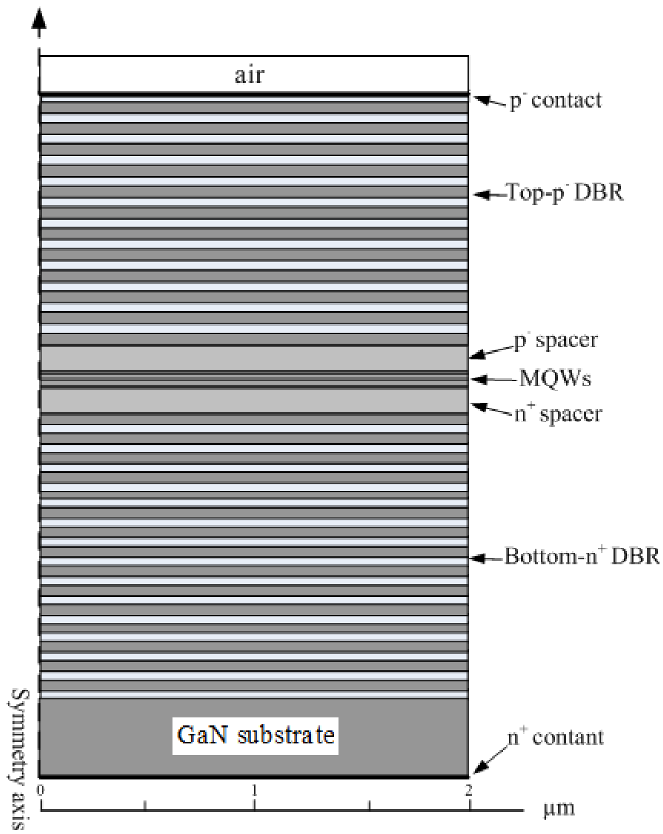

Figure 1. A transverse cross-sectional view of the half portion of 415 nm GaN top surface emitting VCSEL.

$$R = \left(\frac{1 - \left(\frac{n_L}{n_H}\right)^{2n}}{1 + \left(\frac{n_L}{n_H}\right)^{2n}} \right)^2 \quad (1)$$

the low and high refractive indexes of the two layers in DBR, respectively. The DBRs designing criteria are related to maximum optical reflectivity, thermal and electrical conductivity, material index contrast and optical absorption (Saha and Islam 2009). The analysis of DBR in VCSEL design is critical due to its strong reflectivity effect on all laser fundamental properties (Saha and Islam 2009); therefore, the attention paid to the optimized distributed Bragg reflectors, which is very important in VCSEL design (Piprek, 2005). The optimization of the DBR structure is fundamentally important to increase the performance of optical systems based on the VCSEL technology (Song et al., 2000; Jasim et al., 2011).

In this work, integrated system engineering technical computer aided design (ISE TCAD) program for simulation was used to solve the semiconductor and optical wave equations and then to provide the accurate description of the laser device characteristics. The analysis is carried out at room temperature pulsed nitride VCSEL operation of the top-emitting VCSEL structure.

In this paper, the influence of mirror reflectivity on GaN-based vertical cavity surface emitting laser by changing the number of p- type DBRs are investigated in details.

DESIGN OF VCSEL

The ISE TCAD program of laser simulation was used. Transfer matrix method (TMM) with vertical solver is employed to solve the optical and electrical problems inside the VCSEL structure.

The refractive indices of GaN-based ternary alloys using band gap variations (x<0.3) are given by these equations (Zhang et al., 1996; Piprek et al., 2000):

$$n(Al_xGa_{1-x}N) = 2.5067 - 0.43x \quad (2)$$

$$n(In_xGa_{1-x}N) = 2.5067 + 0.91x \quad (3)$$

The band gap energies of the $In_xGa_{1-x}N$ and $Al_xGa_{1-x}N$ ternary alloys at room temperature are (Ferhata et al., 2002):

$$E_{g,In_xGa_{1-x}N} = xE_{g,InN} + (1-x)E_{g,GaN} - 1.43x(1-x) \quad (4)$$

$$E_{g,Al_xGa_{1-x}N} = xE_{g,AlN} + (1-x)E_{g,GaN} - 1.3x(1-x) \quad (5)$$

The effective masses of InGaN active layer used in our simulation can be calculated by the following equations (Fritsch et al., 2003; Cheng and Dutta 2000):

$$m_{e,In_xGa_{1-x}N} = m_{e,GaN} + x(m_{e,InN} - m_{e,GaN}) \quad (6)$$

$$m_{hh,In_xGa_{1-x}N} = m_{hh,GaN} + x(m_{hh,InN} - m_{hh,GaN}) \quad (7)$$

$$m_{lh,In_xGa_{1-x}N} = m_{lh,GaN} + x(m_{lh,InN} - m_{lh,GaN}) \quad (8)$$

where $m_{e,In_xGa_{1-x}N}$ is the effective mass of electrons in $In_xGa_{1-x}N$, $m_{hh,In_xGa_{1-x}N}$ and $m_{lh,In_xGa_{1-x}N}$ are the effective mass of heavy and light holes in $In_xGa_{1-x}N$ respectively. $m_{e,InN}$ is 0.1 m_0 for InN and $m_{e,GaN}$ is 0.151 m_0 for GaN. $m_{hh,InN}$ and $m_{lh,IaN}$ are 1.44 and 0.157 m_0 for InN, respectively, and $m_{hh,InN}$ and $m_{lh,IaN}$ are 1.595 and 0.261 m_0 for GaN, respectively. m_0 is electron mass in free space.

A schematic diagram of 415 nm GaN/AlGaN top surface emitting VCSEL structure is shown in Figure 1. In this design, the device has been constructed with n-GaN substrate followed by n-DBR. In order to get a good performance of device, GaN material at high refractive index ~ 2.5067 and $Al_{0.38}Ga_{0.62}N$ material at low refractive index ~ 2.3433 were used for p and n- type DBRs, respectively. The lower section of the device contains sixty eight pairs of n-DBRs with λ/4 thickness, while the upper section of p-DBR pairs was subsequent remove two mirror pairs in each step from 54 until 34.

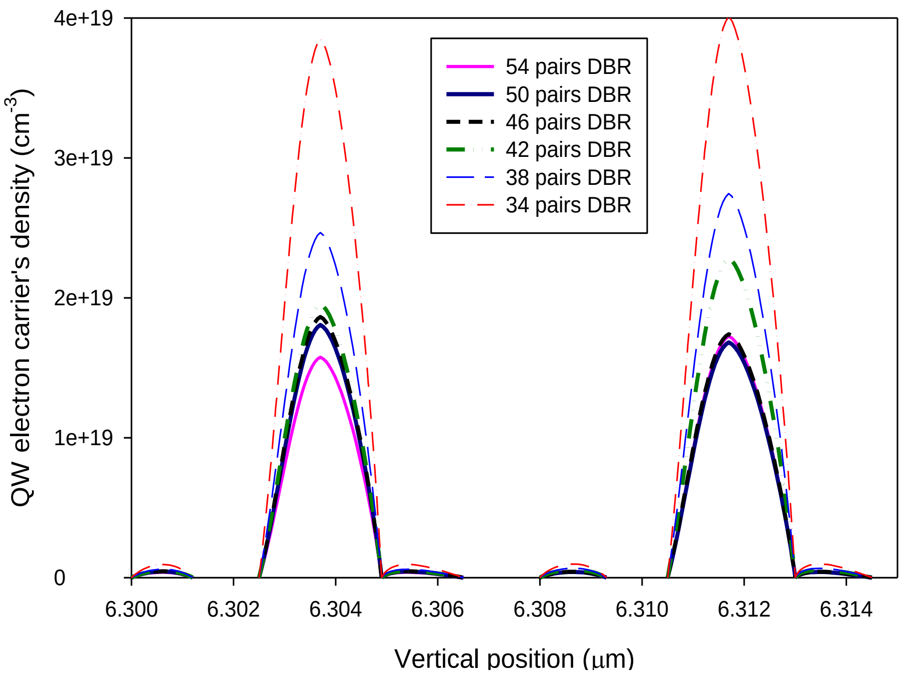

Figure 2. Electron carrier's density distribution inside the MQWs active region as a function of number of p-DBR pairs at a temperature of 300 K.

Since holes have difficulty to move from left to right quantum well due to the relatively large effective mass, low mobility and high band offset in valence band, therefore, the doping concentration of p-DBRs and n-DBRs are proposed to be 5×10^{18} and 5×10^{17} cm^{-3}, respectively, in order to increase the device performance. The active medium for the double quantum well consists three $In_{0.01}Ga_{0.99}N$ barriers and two $In_{0.13}Ga_{0.87}N$ quantum wells. The wells and barriers are sandwiched between cladding layers of $Al_{0.15}Ga_{0.85}N$. The emission wavelength of the VCSELs is about 415 nm.

SIMULATION RESULTS AND DISCUSSION

The effect of reflectivity on the GaN VCSEL performance was investigated by changing of the number of p-DBR pairs by removing two pairs in each step from 54 until 34 subsequently. VCSEL was designed with 68 pairs of bottom n-DBRs with reflectivity of about 99.96%. Figures 2 and 3 illustrated the effect of VCSEL reflectivity of top p-DBRs on carriers' density (electrons and holes) distributed inside the multiple quantum wells (MQWs) active region. The right side of the diagram is n-side and left side is p-side of the GaN VCSEL. The horizontal axis is the distance along the crystal growth direction inside the active medium.

Figures 2 and 3 also showed that electrons and holes carriers' density increased rapidly with decreasing the p-DBR pairs. Optical feedback for the standing wave is provided by DBRs, which is amplified inside the active region, along the longitudinal direction. Stimulated emission is achieved by injecting the carrier concentration into the active region through the surface of the DBRs. Threshold gain occurs where the optical gain equals the total optical loss that is included diffraction loss, absorption, and scattering losses. The reduction of DBR pairs leads to decreasing optical feedback, consequently the carriers' density (holes, electrons) inside the active region increase.

Due to the stimulated emission, the optical field that propagates along the longitudinal direction will be amplified inside the active medium but it will be absorbed in the DBRs. A part of the light will be reflected back into the laser cavity by the DBRs, and the remaining optical field will emit to the surrounding area through the mirrors. Optical material gain inside the quantum well layers increased with decreasing p-DBR pairs of GaN VCSEL, because more carriers' density can be confined inside the active region, and the increase in the probability of stimulated emission in a single pass of the cavity lead to increases on the optical material gain inside the quantum well layers is shown in Figure 4.

Figure 5 shows that output power at 300 K increased to 0.60502, 0.74676, 0.91764, 1.23395, 1.36927, 1.48194 and 1.55595 mW at 54, 52, 50, 46, 44, 42 and 38 p-DBR pairs, respectively, while it decreased to 1.40414 and 0.84305 at 36 and 34 p-DBR pairs. This is occurred because when p-DBR pairs decreased, the coupling losses of mirrors decreased too. Therefore, the probability of stimulated emission in a single pass of the cavity increased due to the increasing in the carriers'

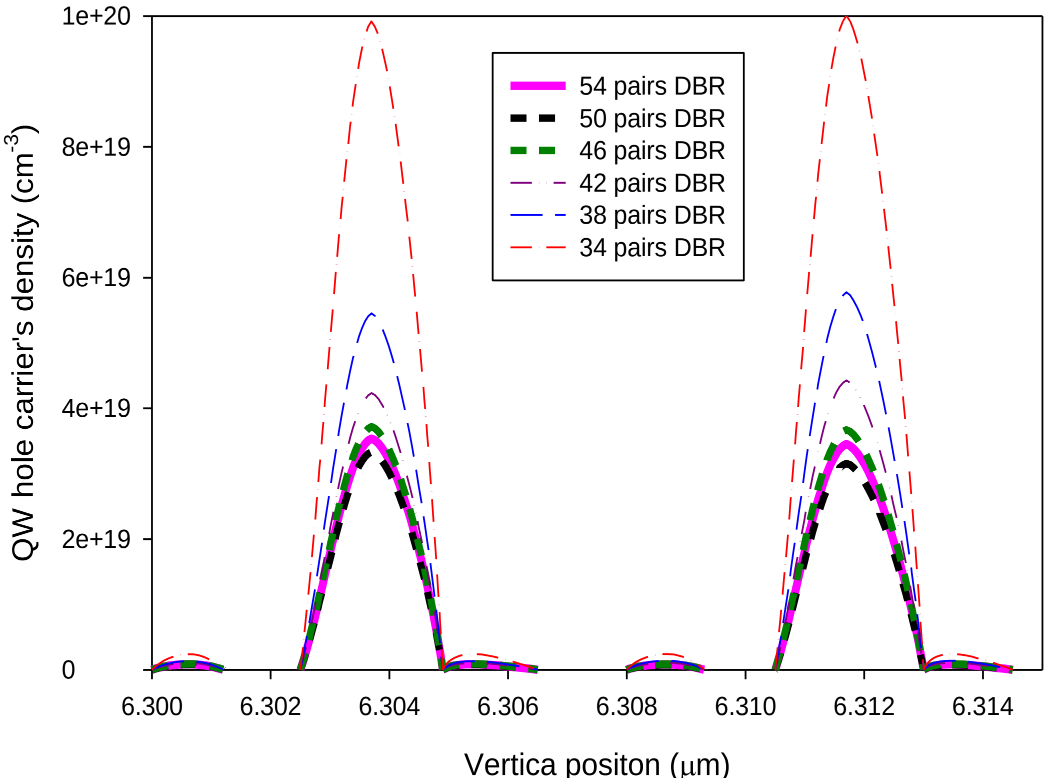

Figure 3. Hole carrier's density distribution inside the MQWs active region as a function of different number of p-DBR pairs at a temperature of 300 K.

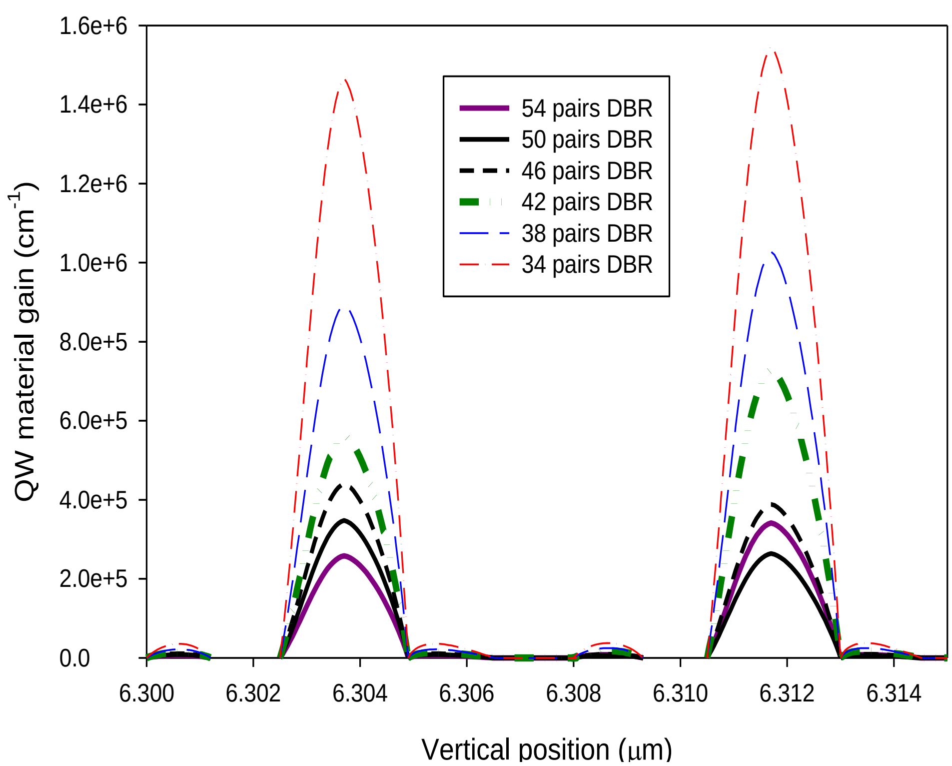

Figure 4. Optical material gain inside MQWs of the VCSEL structure as a function of different number of p-DBR pairs at a temperature of 300 K.

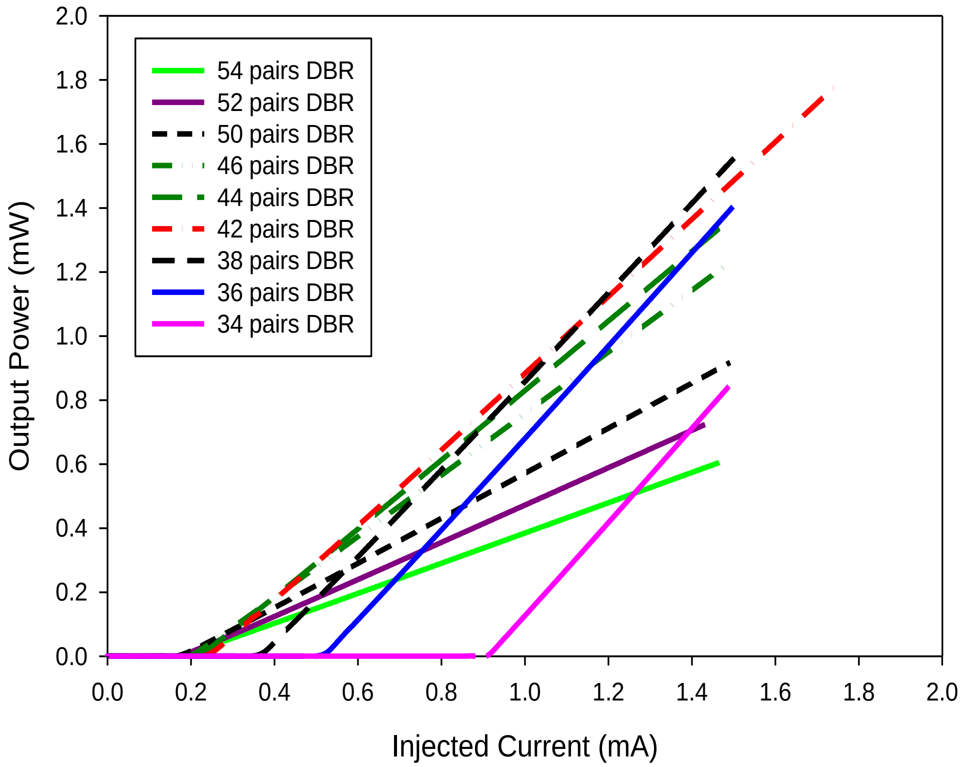

Figure 5. VCSEL output power as a function of injected current with different number of p-DBR pairs.

density (holes, electrons) inside the active region. Therefore, output power was increased. The decreasing in output power at 36 and 34 p-DBR pairs to 1.40414 and 0.84305 mW is attributed to the saturation of the active region by carriers and some of carriers could escape from the MQWs active region, which caused decrease on the output power. In Figure 6, the variation of the slope efficiency *(ΔP/ΔI)*, and maximum output power with output mirror DBR pairs explained that the decreasing on the number of p-DBR pairs until 38 pairs lead to increase the output slope efficiency while it was decreased when the p-DBRs pairs were decreased to be 36 and 32 due to same mentioned reasons.

Figure 7 shows VCSEL threshold current and differential quantum efficiency (DQE) as a function of different number of p-DBR pairs. The threshold current was increased with decreasing the number of p-DBR pairs due to the increasing number of carriers inside the active region, this leads to increase in the diffraction losses and scattering between the carriers inside active region, which caused to increase of the heat inside the VSCEL structure. It was found that the DQE was decreased when the number of DBR pairs is increased due to increase of optical losses (absorption and scattering losses of mirrors) as well as the heat generated by electrical series resistance of the DBR pairs made the efficiency of the device less.

Conclusion

This work investigated the number of DBR effects (reflectivity) on the GaN-based VCSEL performance. The numbers of p-DBR pairs subsequent remove two pairs in each step from 54 until 34. The simulation results indicated the carriers' density enhancement with decrease in the p-DBR pairs of VCSEL. It is due to the decreasing of the optical feedback of mirrors that leads to increase in the carriers' density (holes, electrons) inside the active region. Consequently, the more carriers' density can be confined inside the active medium. With decreasing p-DBR pairs of GaN-base VCSEL, the optical material gain inside the quantum well layers increased due to the increase in probability of stimulated emission in a single pass of the cavity which increased the gain inside the MQWs active region. Therefore, output power was increased. At 36 and 34 p-DBR pairs, because of the saturation of the active region by carriers, some of carriers would escape from the MQWs active region and output power decreased. Also, it was found that by increasing the number of DBR pairs, the output slope efficiency and DQE decreased, due to increasing of optical losses (absorption and scattering losses of mirrors) as well as the heat generation by electrical series resistance of the DBR pairs which made the efficiency of the device less.

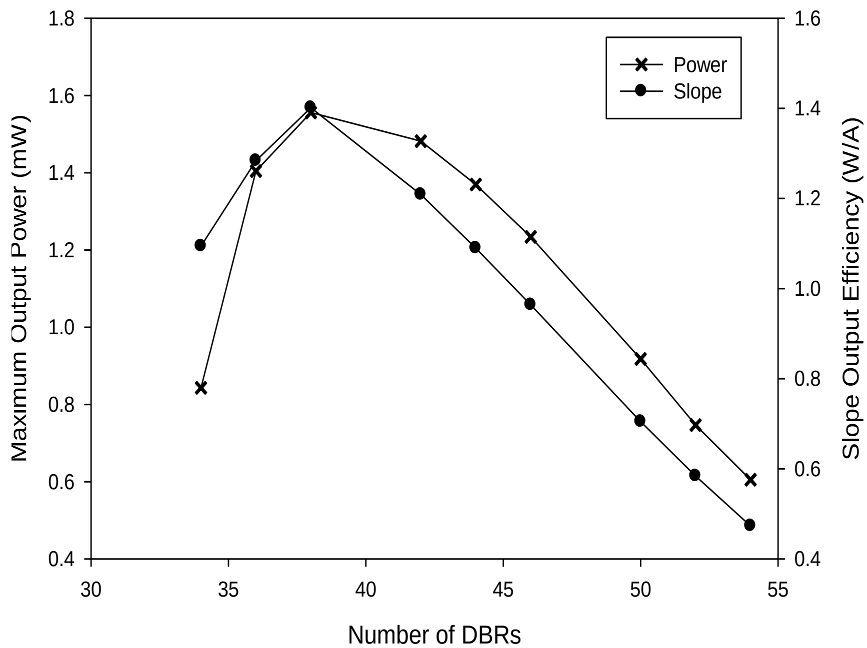

Figure 6. VCSEL maximum output power and slope output efficiency as a function of different number of p-DBR pairs at a temperature of 300 K.

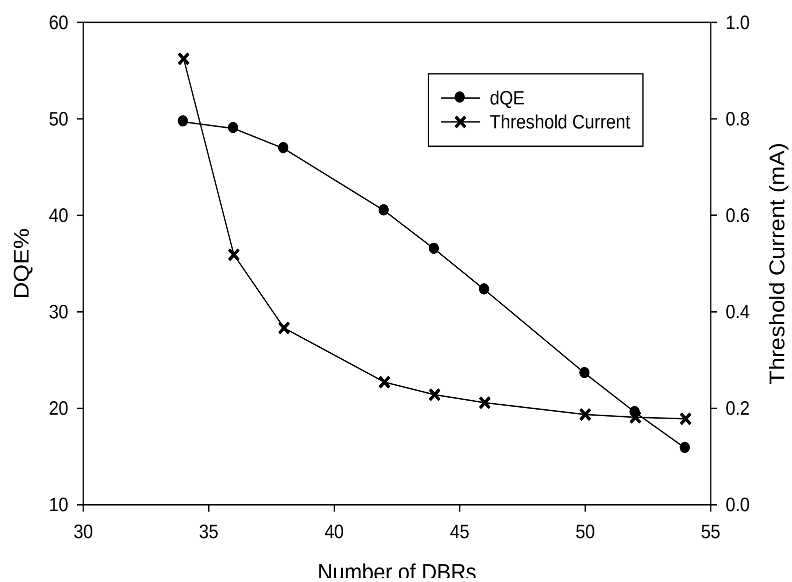

Figure 7. Threshold current, differential quantum efficiency as a function of different number of p-DBR pairs at a temperature of 300 K.

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