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Number of Quantum Well(s) Effects on GaN-Based VCSELs

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Abstract

Advanced numerical simulation program was used to analyze the performance of GaN based vertical cavity surface emitting laser (VCSEL) with single, double and triple quantum well(s) as active region. It was found that numbers of quantum well (QW) variation inside the active region is the most critical factor on the VCSEL performance. The lowest threshold current and highest in both the slope efficiency and differential quantum efficiency were observed when the well number is double (DQWs) at 415 nm VCSEL. This is ascribed to that for single quantum well (SQW), some of the gain begin to escape before lasing is achieved while for triple quantum wells (TQWs) while are separated by many thick barriers, then transport carriers between wells will be inefficient. As a result, a non-uniform carrier distribution may result.

تأثير عدد ابار الكمي على الليزرات ذات الانبعاث الشاقولي

الخلاصة

تم استخدام برنامج المحاكاة العددية المتقدمة لتحليل أداء ليزرات غاليوم نترايت (GaN) ذات انبعاث سطحي لتجويف شاقولي (VCSEL), وباستخدام أبار كميه واحدة, ثنائية وثلاثية كوسط فعال. وجد أن تباين أعداد الابار (QW) في داخل المنطقة الفعاله هو العامل الأكثر أهميه على أداء هذه الليزرات. لقد تم الحصول على ادنى تيار عتبة وأعلى كفاءة ميل و كفاءة تفاضلية كميه عندما كان عدد الابار مزدوجا (DQWs) عند الطول الموجي 415 نانومتر. ويرجع ذلك إلى أنه بالنسبة لبئر واحد (SQW)، يبدأ بعض الربح بالهروب من الوسط الفعال قبل الحصول على الليزر . أما في الآبار الكميه الثلاثية (TQWs) ، لأنها مفصولة بحواجز سميكة كثيرة، لذلك يكون نقل حاملات الشحنة بين هذه الآبار غير فعال. مما ينتج عنه توزيع غير منتظم لهذه الحاملات.

Introduction

VCSEL with quantum well active region takes advantage of quantization of movement of carrier's confinement in very thin heterostructures [1]. The VCSEL shows a number of interesting properties which included the low threshold current and threshold current density due to the small volume, and as a result the carrier density required to achieve population inversion is small [2-5]. The ISETCAD simulation
Program was used to analyze the performance of GaN-based VCSELs. A VCSEL consist of an active region sandwiched between two distributed Bragg reflectors (DBRs). For the investigation of the number of quantum wells on the laser performance, we considered three cases, single quantum well, double and triple quantum wells. It was found that numbers of QW variation inside the active region is the most critical effect on the VCSEL threshold current, slope efficiency and differential quantum efficiency (DQE).

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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. A transverse cross-sectional view of the half portion of 415 nm GaN top surface emitting VCSEL is shown in Fig. 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, while the upper section of p-DBR pairs was forty two pairs with $\lambda/4$ thicknesses. 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} cm^{3} and 5×10^{17} cm^{-3}, respectively. The active medium consists of $In_{0.01}Ga_{0.99}N$ as a barrier and $In_{0.13}Ga_{0.87}N$ as a quantum well. The well and barriers are sandwiched between two cladding layers of $Al_{0.15}Ga_{0.85}N$. The emission wavelength of the VCSELs is about 415 nm and the radius of the device is 1 µm.

Simulation results and discussion In order to study the effect of well umber extremely; the well number was changed from 1 to 3 layers. For the preliminary VCSEL structure under confinement of two barriers as well as two spacer layers is not enough. Since study, the electrical field inside the active medium for SQW, DQWs and TQWs are shown in Fig. 2.

In Fig.2 the right side of diagram is n-type side and the left side is the p-type side of VCSEL. The horizontal axis is the distance along the crystal growth direction. It was observed that TQWs has lower electric field and electrostatic potential compared to SQW due to reduction of heat generation by carriers scattering and the reduction of diffraction losses inside the active region.

Fig. 3 and Fig. 4 illustrated the effect of carriers' density (electrons and holes) distribution inside the SQW, DQWs and TQWs active region, respectively. The maximum carrier distribution was obtained inside the GaN well layers. This accumulation in carrier was achieved by the band gap profile. Increase in the number of the carrier density (electrons and holes) cause increase in the scattering and diffraction losses between carriers inside the SQW active medium. Increasing in the number of the carrier density (electrons and holes) also leads to increase in probability of stimulated emission in a single pass of the cavity; therefore optical material gain was increased inside SQW as shown in Fig. 5. But although the optical material gain inside SQW is more than DQWs, we observed that output power of DQWs is more than SQW and TQWs as shown in Fig. 6. This indicate that for SQW, some of the gain begins to escape before lasing is achieved (band filling if the SQW is filled with carriers) due to the leakage of carriers out of the active layers because the TQWs structure has wells separated by many thick barriers, then transport between wells will be inefficient. As a result, a non-uniform carrier distribution may result. Meanwhile, the threshold current density and carrier overflow increase with increasing well numbers. Fig. 7 shows laser threshold current and maximum output power as a function of well numbers. We observed lowest threshold current and highest output power when the well number is two at VCSEL cavity. The decrease in laser threshold current to 0.252 mA and increase the output power to 148 mW for DQWs are attributed to the uniform carrier distribution inside the active region An increase for both of the output slope efficiency and differential quantum efficiency (DQE) of the device were observed for DQWs as shown in Fig. 8. This is attributed to the reduction of the threshold current, which causes a reduction of the heat generation and thus increase in the overall performance of the device.

Conclusions

Theoutputperformance of GaN VCSELs using ISETCAD simulation program is numerically investigated. Lowest threshold current and highest in output power and both of slope efficiency, and differential quantum efficiency were observed when the well number is DQWS VCSEL with λ-cavity. This is ascribed to that for SQW, some of the gain begins to escape, while for TQWs, the non uniformity of carriers injected is increased. Meanwhile, the threshold current density and carrier overflow increase with increasing well numbers.

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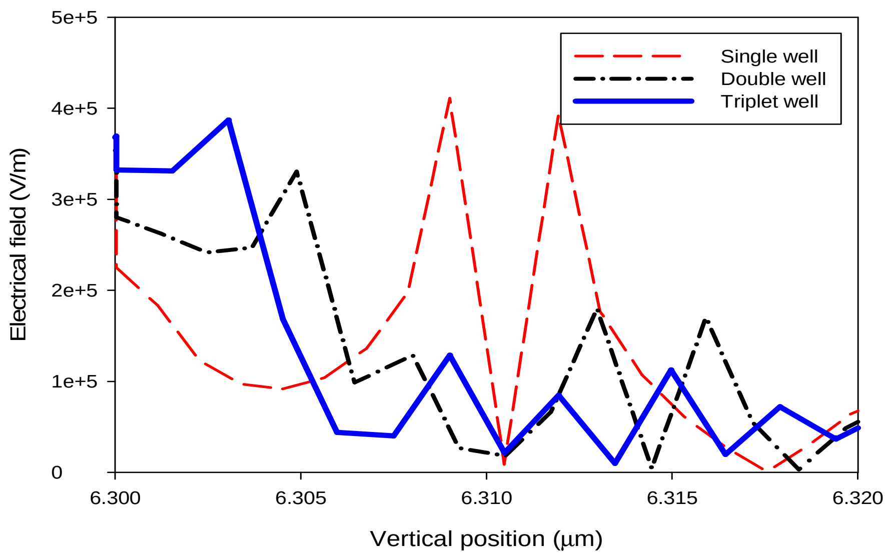

Figure 1: A transverse cross-sectional view of the half portion of 415 nm GaN top surface emitting VCSEL [6-9].

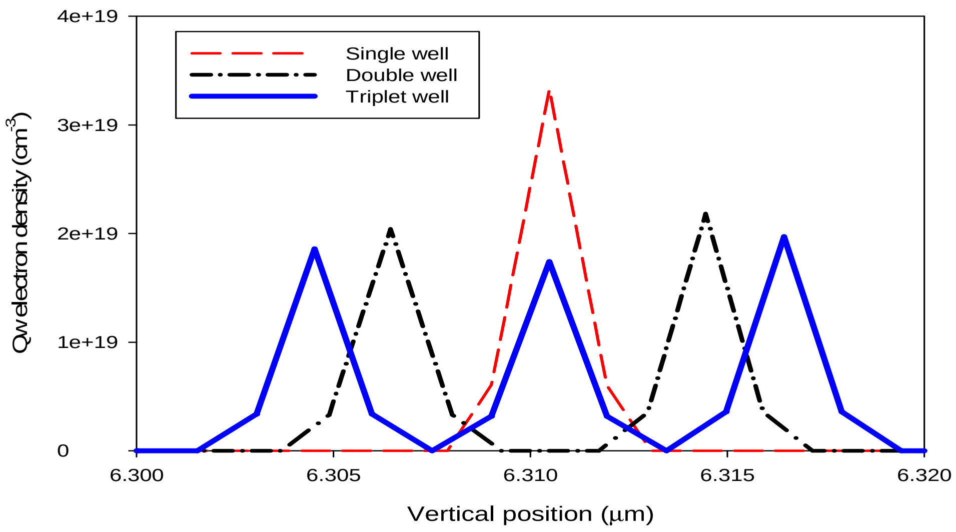

Figure 2: The electric field inside the active medium with SQW, DQWs and TQWs.

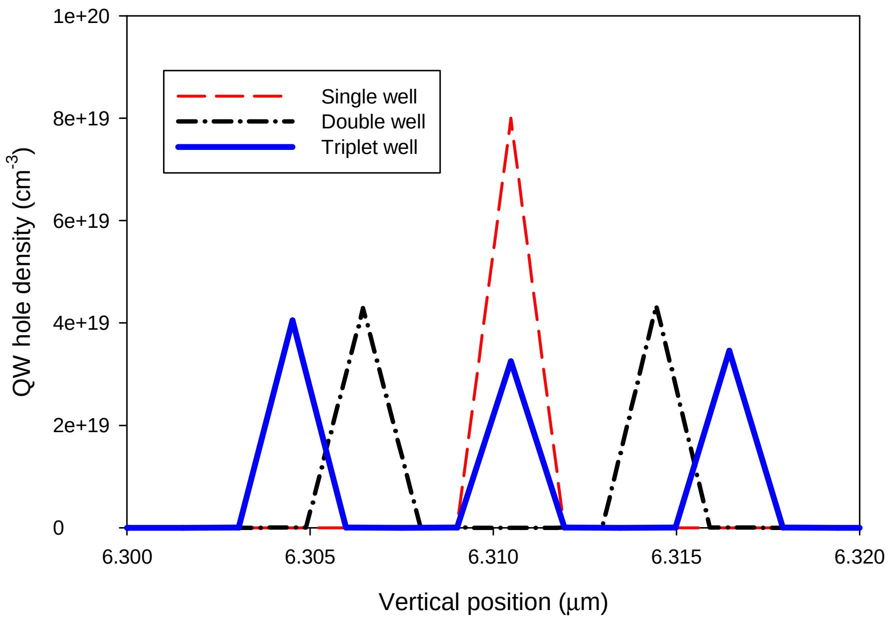

Figure 3: Electron carrier's density distribution inside the SQW and DQWs and TQWs active region at temperature of 300 K.

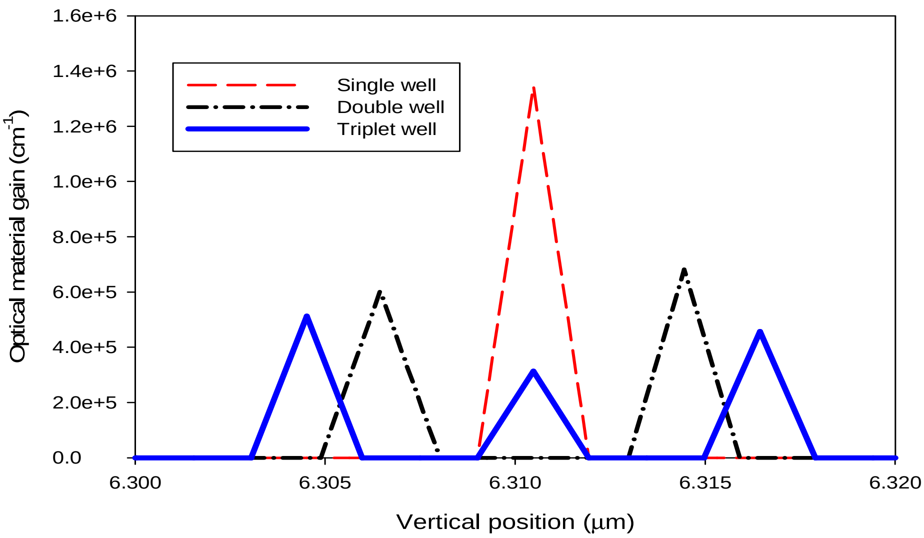

Figure 4: Hole carrier's density distribution inside the SQW and DQWs and TQWs active region at temperature of 300 K

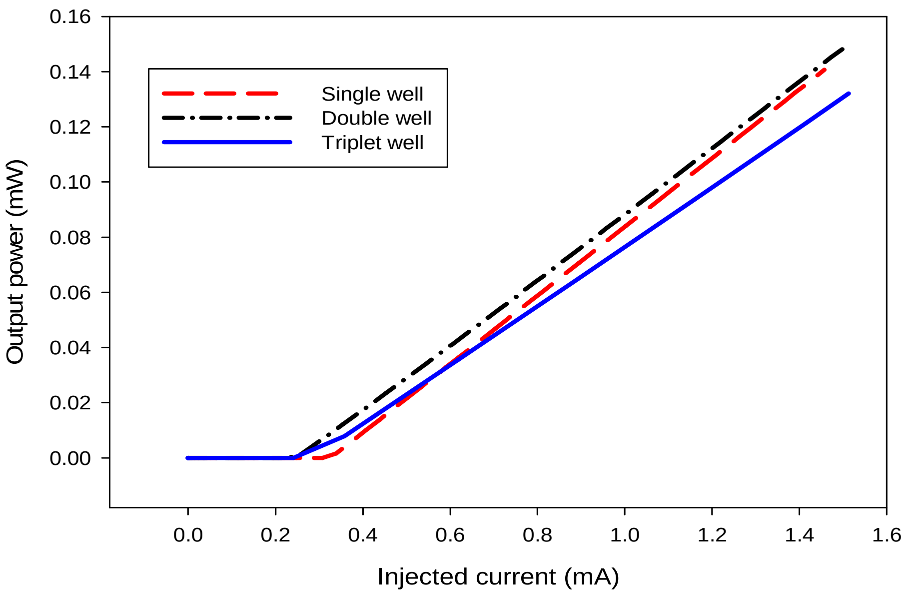

Figure 5: Optical material gain inside the SQW and DQWs and TQWs

active region at temperature of 300 K.

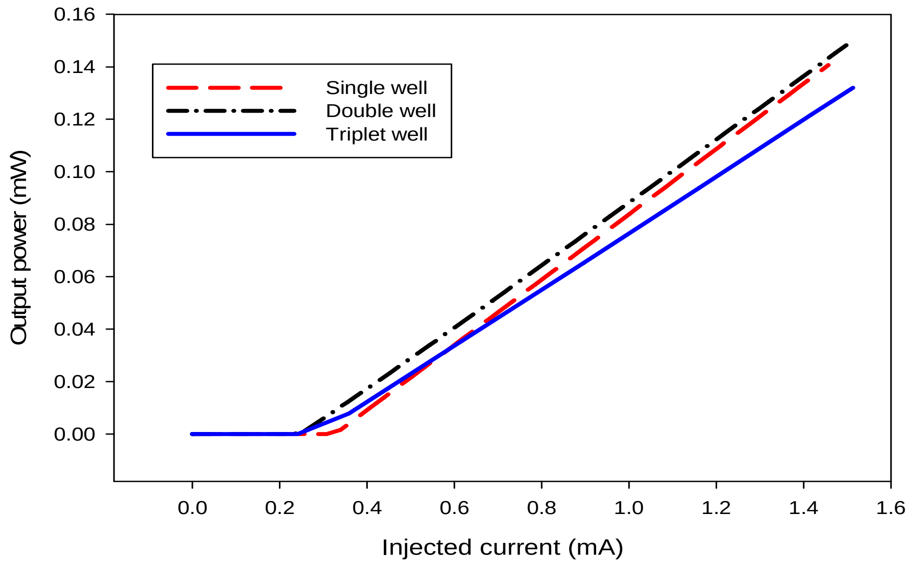

Figure 6: Laser output power of SQW, DQWs and TQWs GaN active region at temperature of 300 K.

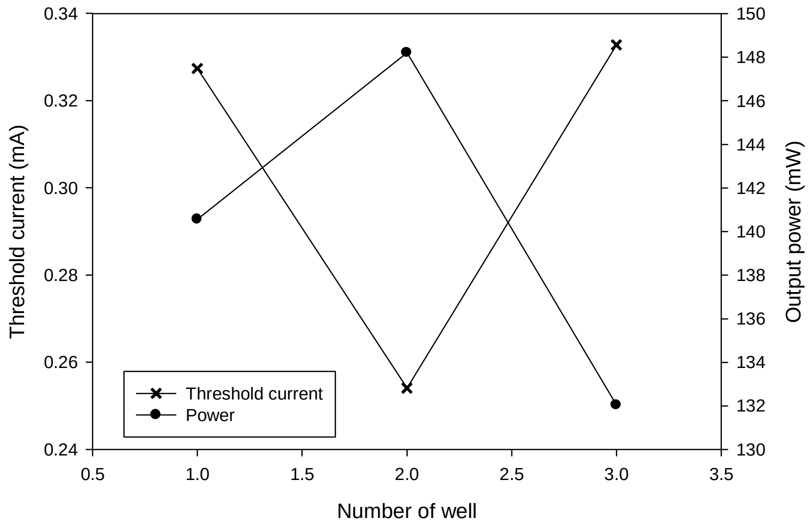

Figure 7: Laser threshold current and output power as a function of well numbers.

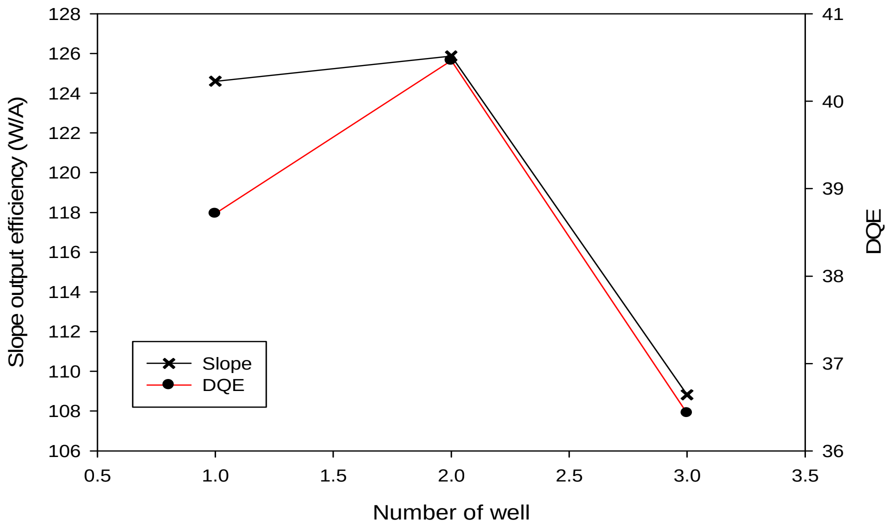

Figure 8: Slope efficiency, and differential quantum efficiency (DQE) as a function of well numbers.