Simulation of InGaN violet and ultraviolet multiple-quantum-well laser diodes

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- Motivation
- Introduction
- Simulation structure and parameters
- Results and discussion
- Conclusion

Motivation

- In our previous work, the laser performance of 400–480 nm InGaN laser diodes had been studied.
  (Y.-K. Kuo *et al.*, Opt. Communi., 231, 395, 2004.)
- The simulation results showed that the lowest threshold current of the InGaN QW lasers is obtained when the number of QWs is two if the wavelength is shorter than 450 nm, and one if the wavelength is longer than 450 nm.
- The experimental results showed that the lowest threshold currents of the InGaN QW lasers with an emission wavelength of 390–420 nm were obtained when the number of QWs was two.
  (S. Nakamura, *et al*., Jpn. J. Appl. Phys. 37, L1020, 1998.)
- In this work, the performance of the laser diodes of various active region structures, operating in a spectral range from 385 to 410 nm, are investigated.

- Short-wavelength III-V semiconductor laser diodes and light-emitting diodes (LEDs) have been extensively studied and developed for high-density optical storage systems.
- GaN-based violet laser diodes with emission wavelength around 405 nm have attracted much interest due to its application in next-generation digital versatile disk.
- High power violet laser diodes have been studied by several research groups (Asano *et al*. 2002; Skierbiszewski *et al*. 2005).
- The ultraviolet laser diodes have been investigated due to their potential applications of the bioagent detection system, UV curing and sterilization (Kneissl *et al*. 2003; Nakamura *et al*. 2001).

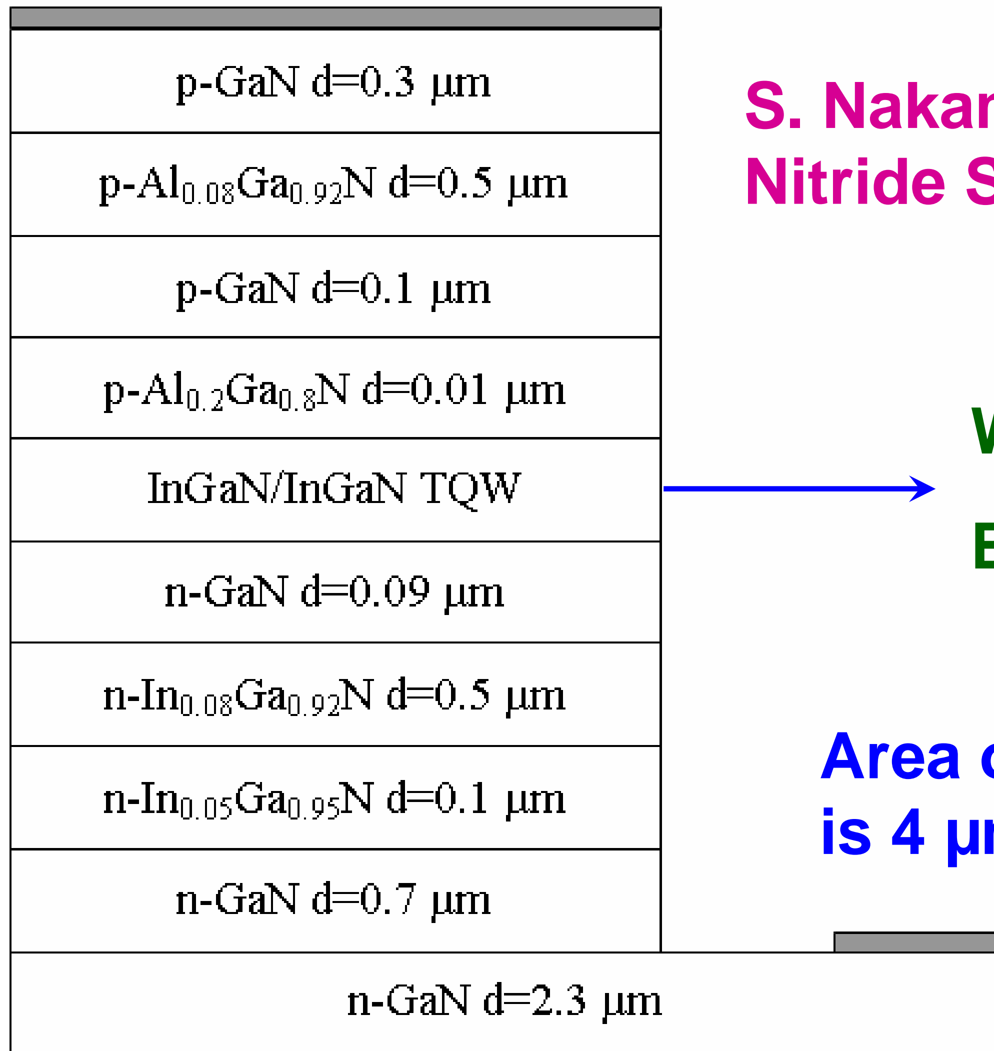
Introduction

- In order to obtain good temperature stability of emission wavelength, a high characteristic temperature, T_0, is usually desired for a laser diode.
- The reported values of characteristic temperatures are typically ranging from 81 to 190 K (Kneissl *et al*. 2000; Kneissl *et al*. 1999; Sasaoka *et al*. 2006).
- However, quite recently, a characteristic temperature of as high as 302 K for an InGaN laser diode with an emission wavelength of 415 nm has been demonstrated (Świetlik *et al*. 2006).

Introduction

- In this work, the optical properties of the violet and ultraviolet (385–410 nm) InGaN MQW laser diodes are numerically studied with a LASTIP (abbreviation of LASer Technology Integrated Program) simulation program.
- The threshold currents of laser diodes with different quantum-well structures, which have different emission wavelengths, are studied.
- Since the characteristic temperature of a laser diode can be closely related to the number of quantum wells, the characteristic temperatures for the laser diodes with various active layer configurations are investigated and compared.

Structure



S. Nakamura, MRS Internet J. Nitride Semicond. 2, 5 (1997).

Well:$In_{0.16}Ga_{0.84}N$

Barrier:$In_{0.02}Ga_{0.98}N$

Area of the ridge geometry is 4 μm × 550 μm.

Parameters

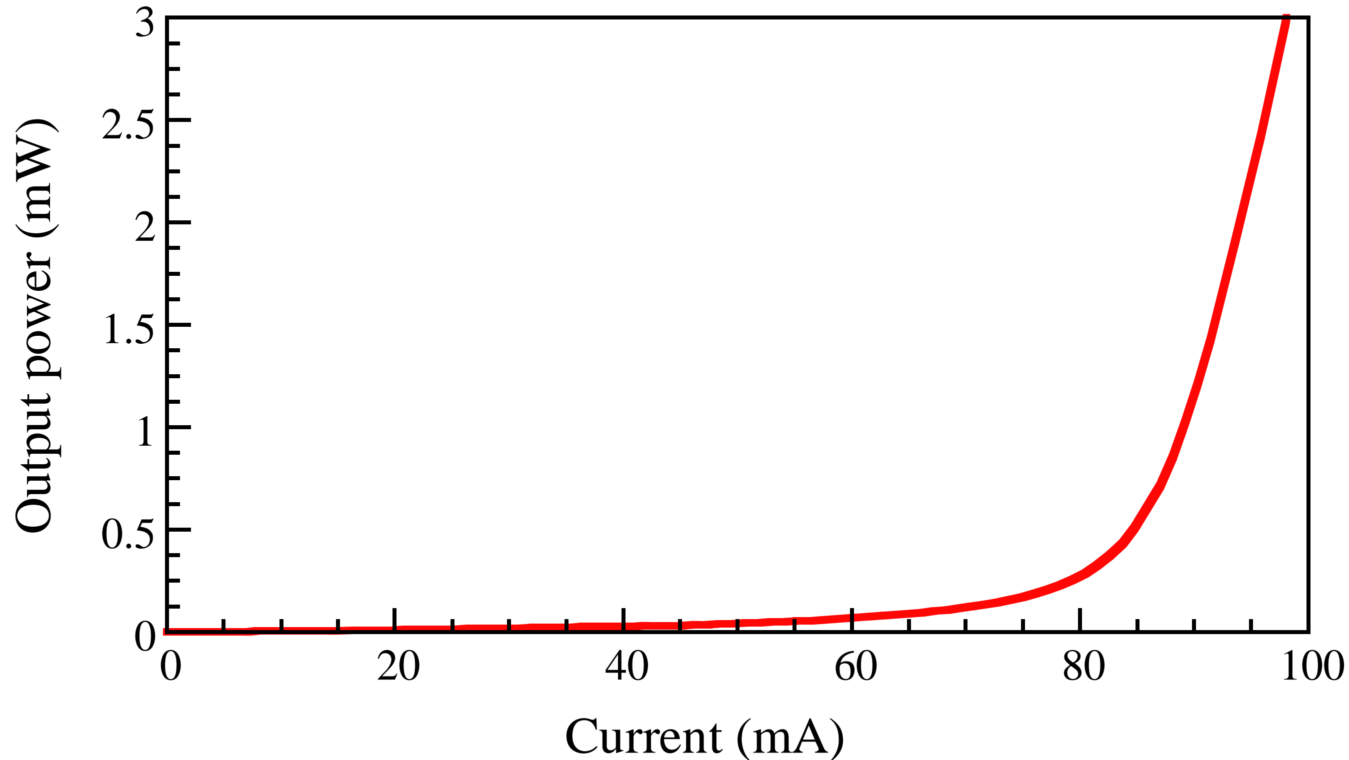
- Band gap energy of $In_xGa_{1-x}N$:

$$E_g(x) = E_{g,InN} \cdot x + E_{g,GaN} \cdot (1-x) - b \cdot x \cdot (1-x)$$

$E_{g,InN}$: 0.77 eV; $E_{g,GaN}$: 3.42 eV; b: 1.43 eV

- SRH recombination lifetime: 2.35×10^{-9} s
- Internal loss: 4500 m^{-1}

L-I curve



➢The L-I curve is obtained when the original TQW structure is used.

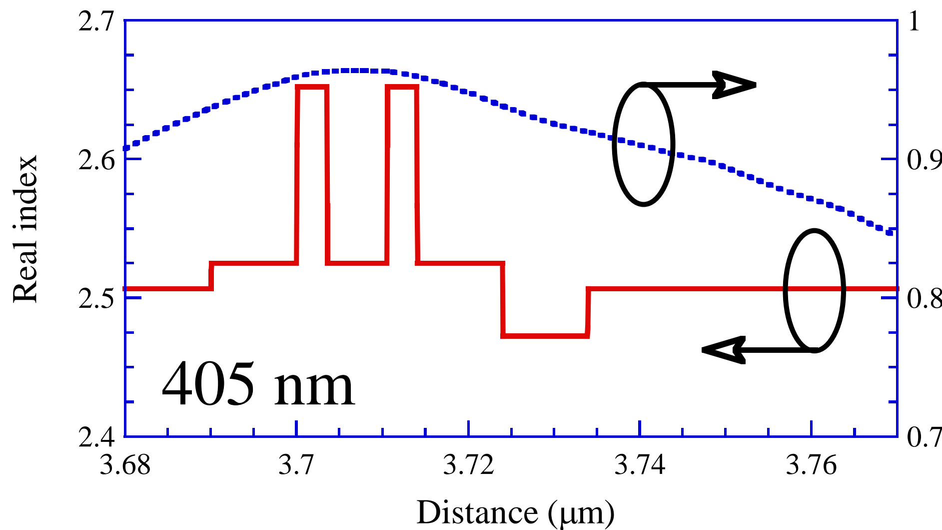
➢The emission wavelength of the TQW structure is 405 nm.

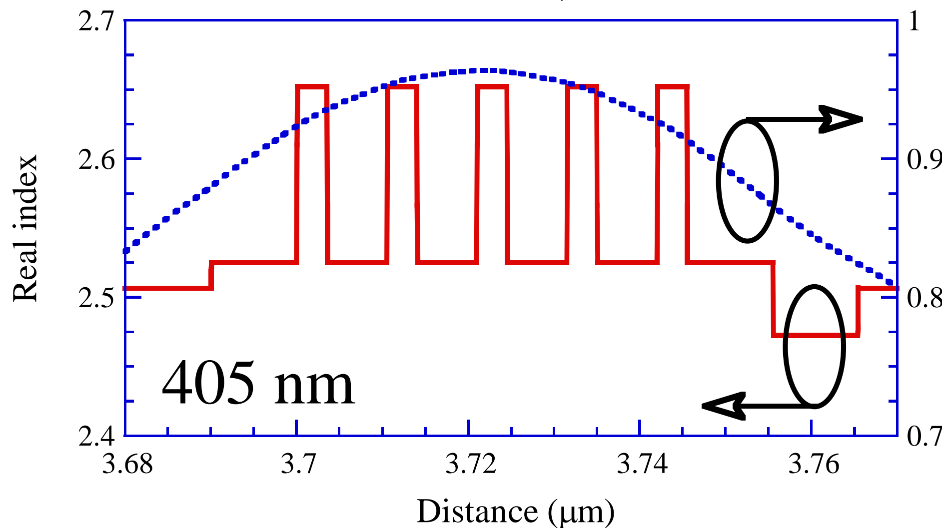
Threshold current versus wavelength

Number of QWs	Emission wavelength (nm)				
	385	390	397	405	410
	Threshold current (mA)				
1	168.04	116.60	99.55	94.02	93.92
2	99.15	87.18	79.37	77.33	76.69
3	105.95	94.68	90.96	86.00	83.34
4	119.67	106.81	104.37	97.81	93.31
5	134.99	120.86	118.97	111.85	106.61

In addition to 385-410 nm, simulations were also conducted for laser diodes with an emission wavelength of less than 385 nm; however, the threshold currents were high due presumably to small conduction band offsets.

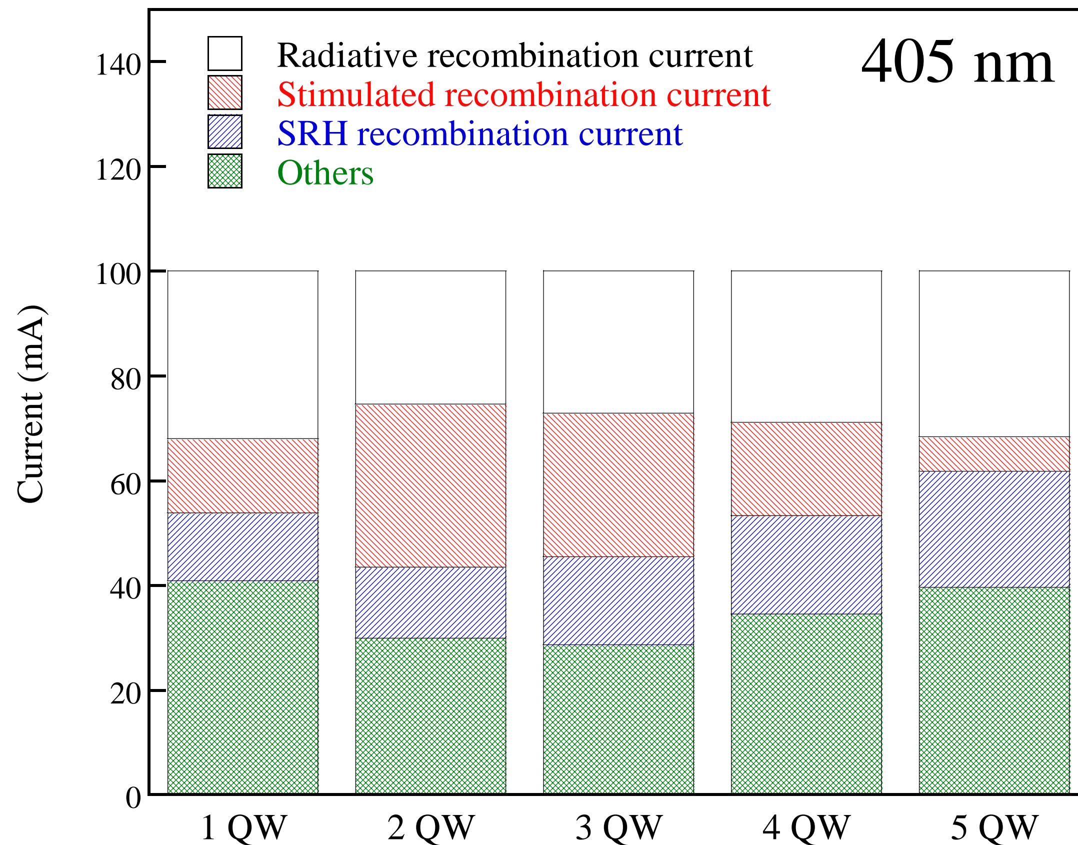
Wave intensity & Real index





- The wave intensity in the active region of **DQW structure** is higher than that of **five-quantum-well** structure.
- Therefore, the **DQW structure** has higher optical field than that of **five-quantum-well** structure.

Recombination current



Current density

Width of active region

$$J = q \cdot (R \cdot d)$$

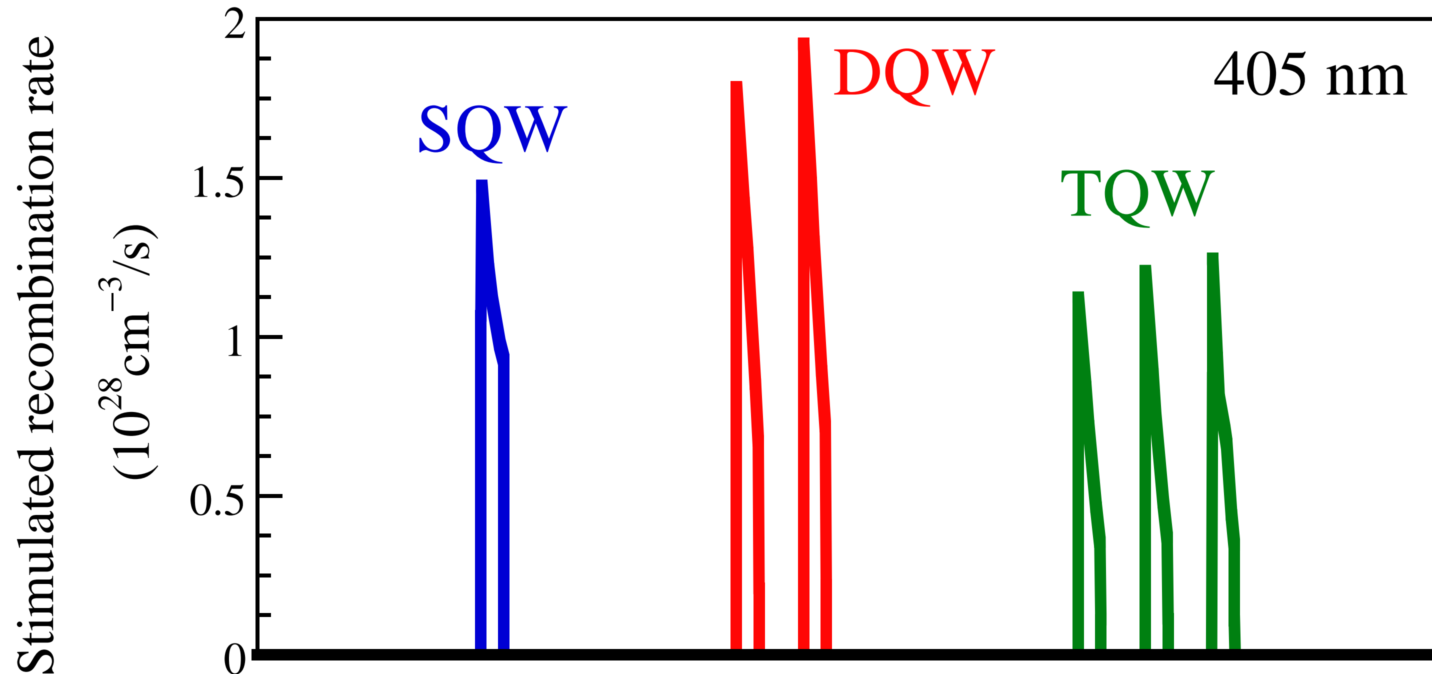
Recombination rate

$$I = J \cdot w \cdot L$$

Area of the ridge geometry

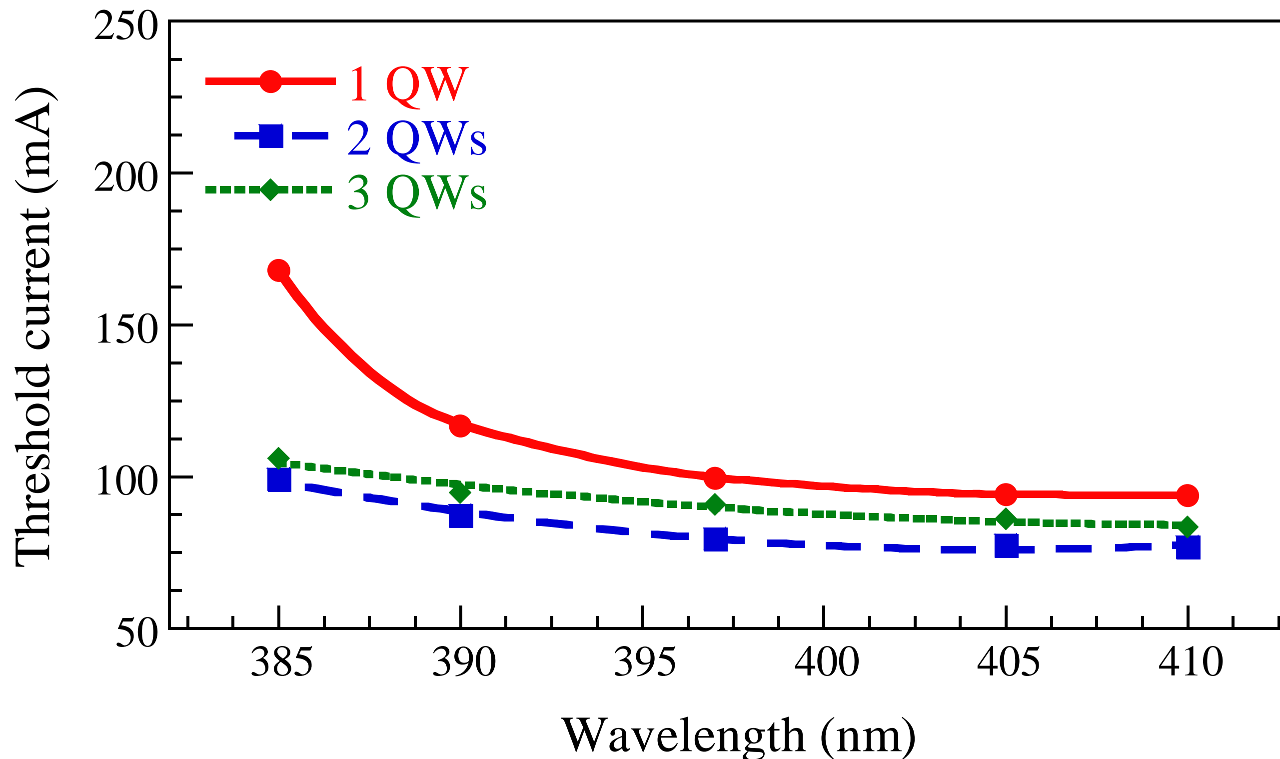
The stimulated recombination current is about 31.13% of the total current for the DQW laser structure and 6.57% of the total current for the five-quantum-well laser structure.

Stimulated recombination rate



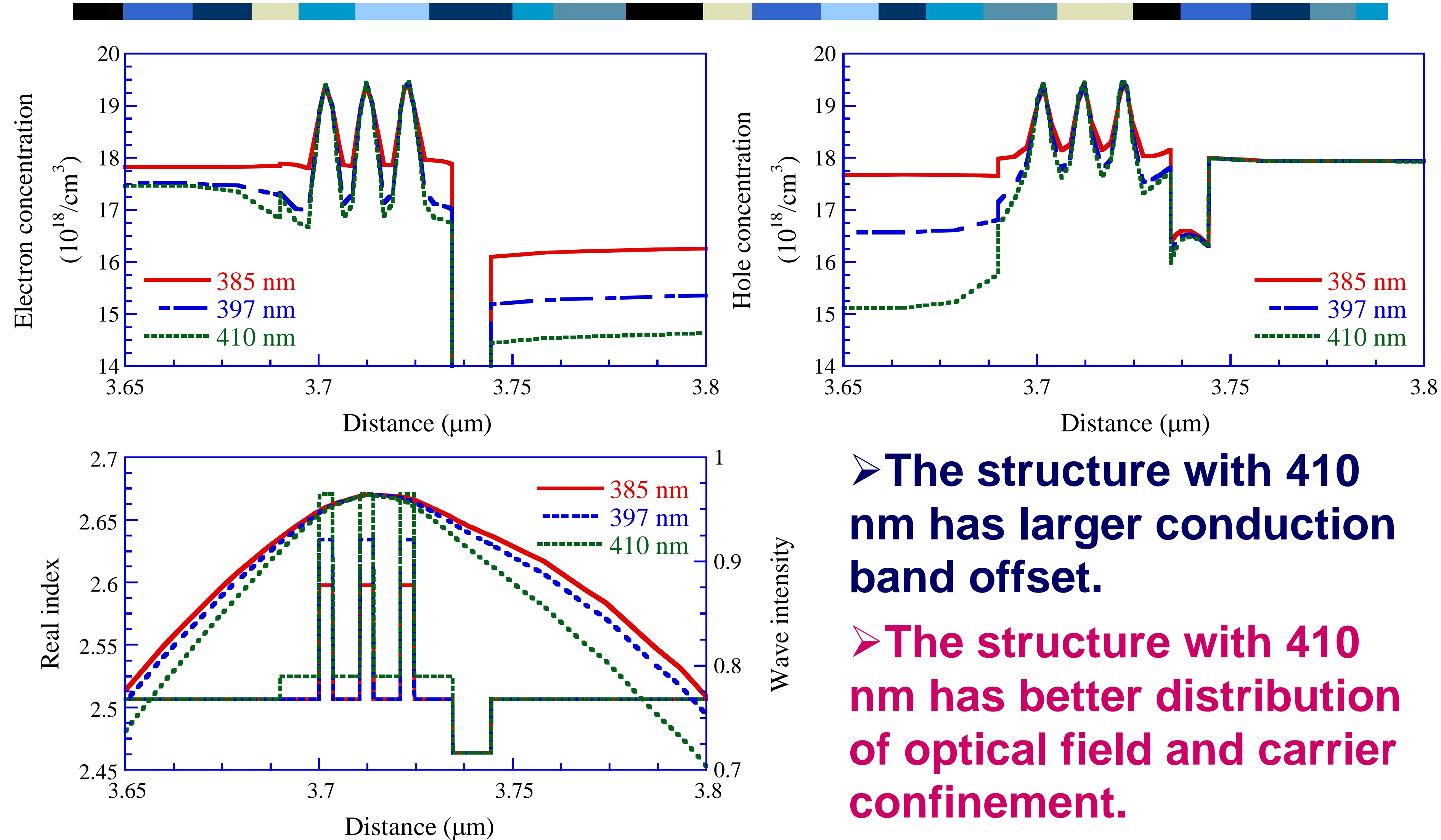
It indicates that the DQW structure has the best stimulated recombination distribution which may be caused by effective carrier and optical confinements in the active region.

Threshold current versus wavelength



- ➢The simulation results indicate that the laser structure has the lowest threshold current when the **number of quantum wells is two**.
- ➢Similar results were also observed by experiment. (Nakamura et al. 1998).

Carrier concentration & wave intensity



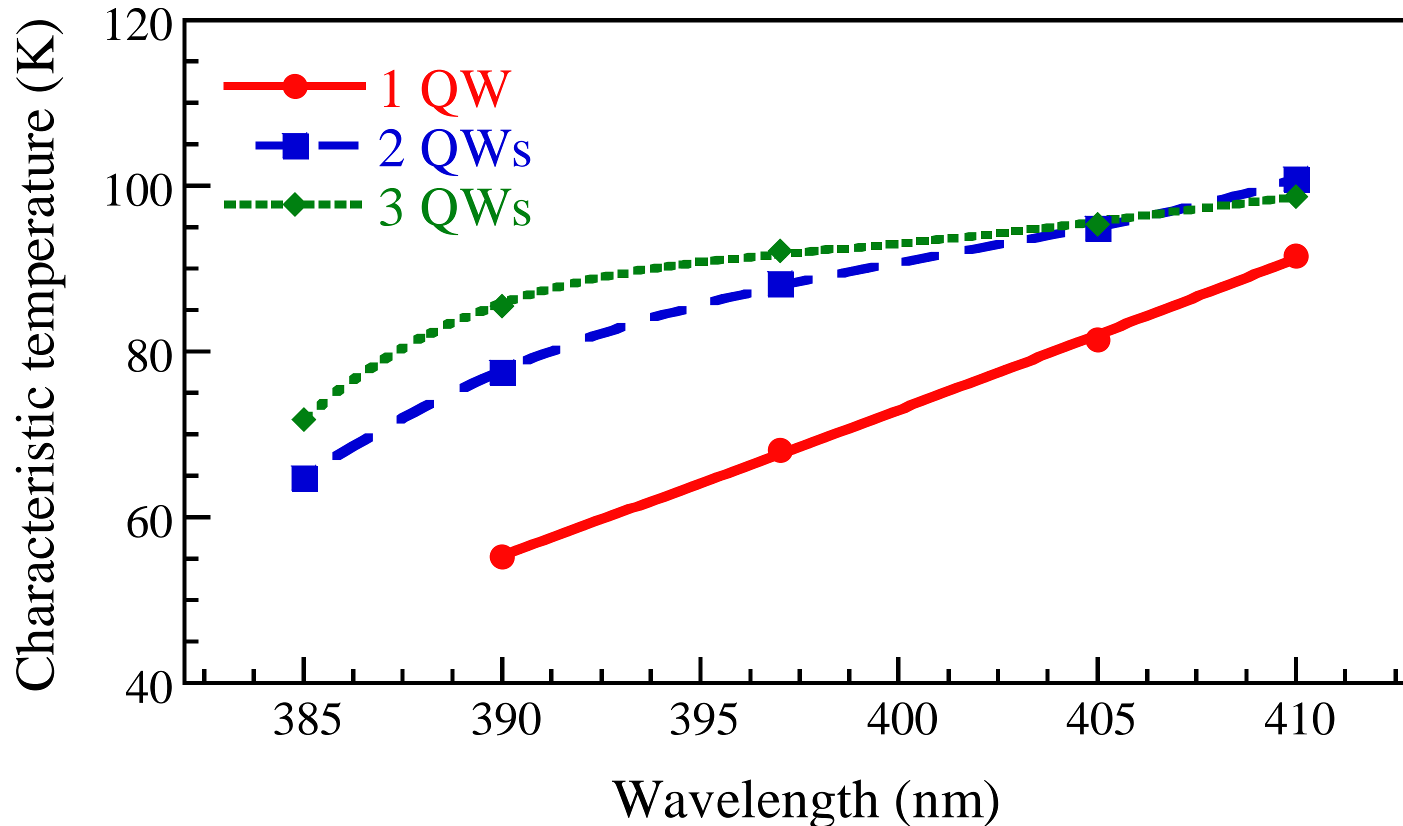
- The structure with 410 nm has larger conduction band offset.
- The structure with 410 nm has better distribution of optical field and carrier confinement.

Characteristic temperature versus wavelength

Number of QWs	Emission wavelength (nm)				
	385	390	397	405	410
	Characteristic temperature (K)				
1		55.27	68.14	81.44	91.52
2	64.84	77.47	88.21	94.91	100.87
3	71.85	85.46	92.17	95.40	98.68

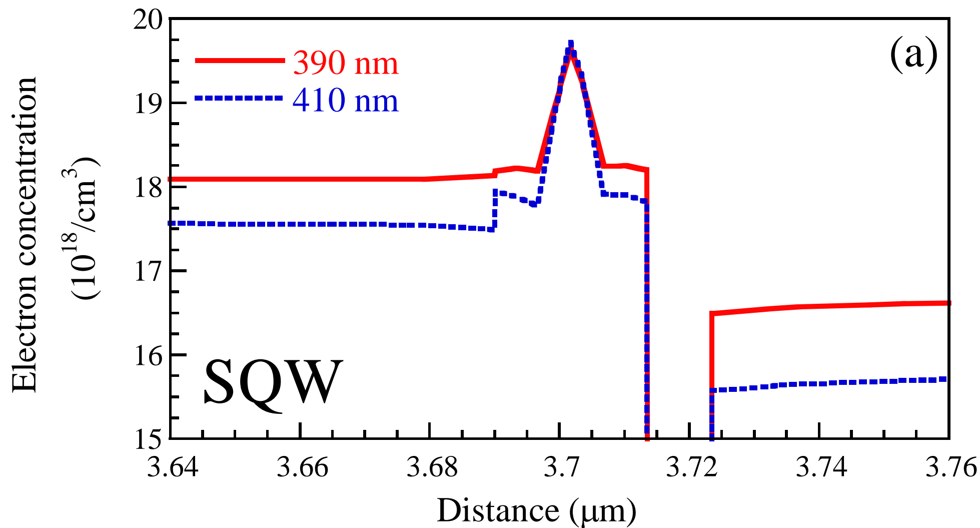
- **According to the equation , $I_{th} = I_0 \cdot e^{(T/T_0)}$, the characteristic temperature T_0 can be obtained.**
- **It can be found that the smallest characteristic temperature is obtained when the number of quantum well is one.**

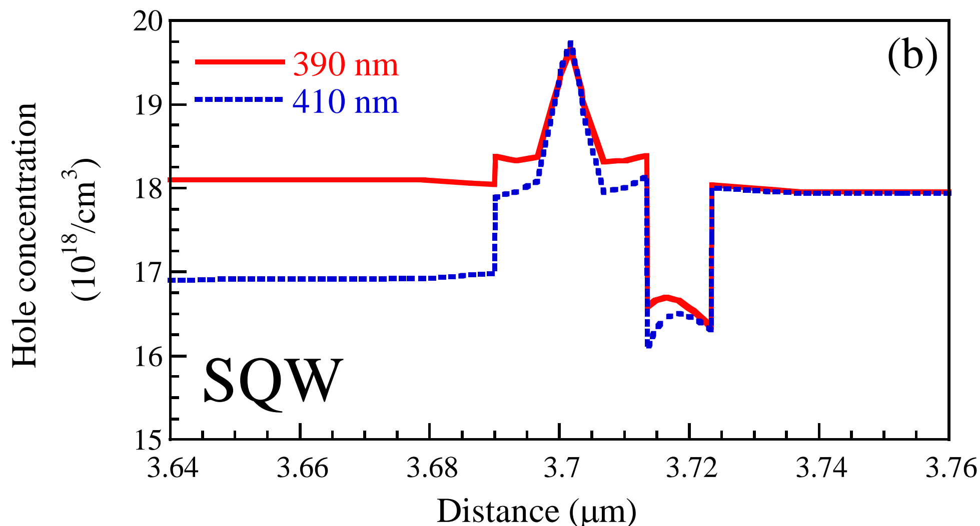
Characteristic temperature versus wavelength



The DQW structure has the largest T_0 when the wavelength is larger than 405 nm, while the TQW structure possesses the largest T_0 when the wavelength is smaller than 405 nm.

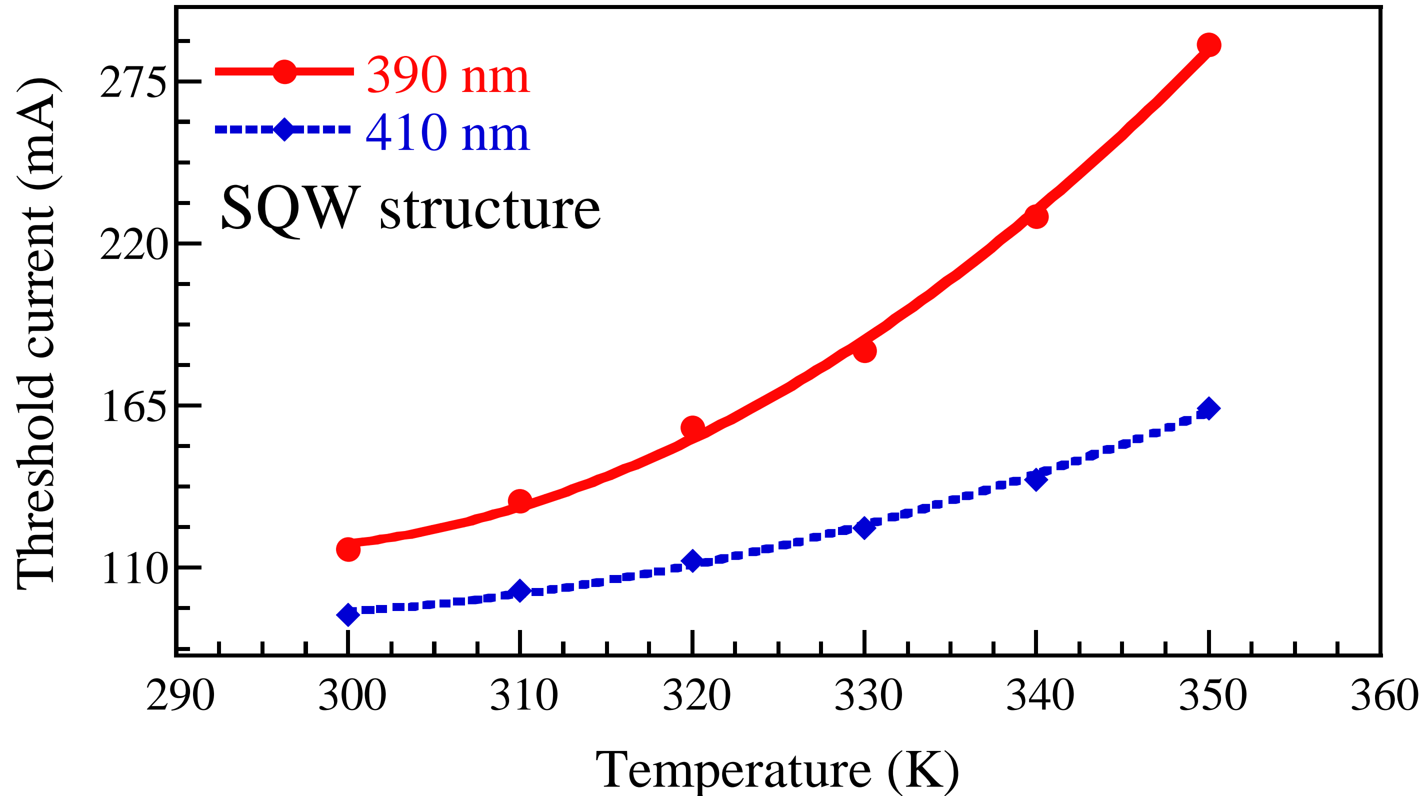
Carrier concentration





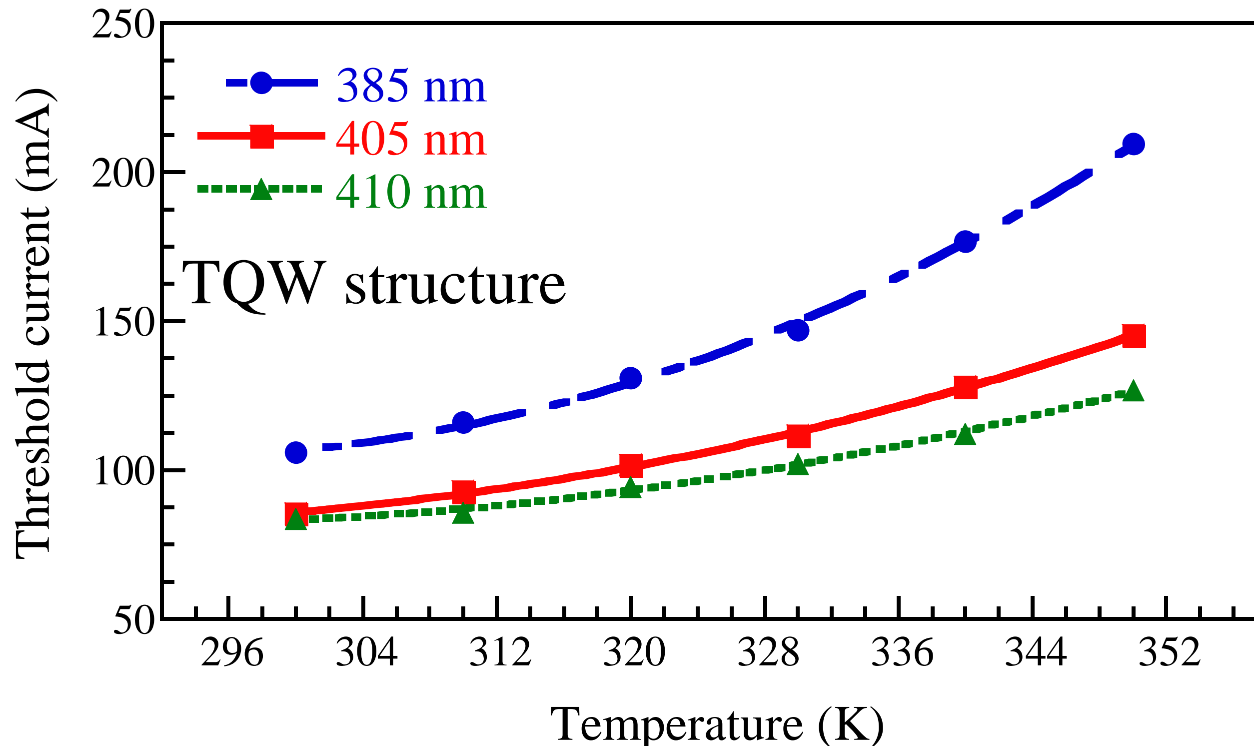
- **The carrier confinement at 410 nm is better than that at 390 nm.**
- **Therefore, the leakage carriers and non-radiative recombination at 390 nm are higher than those at 410 nm.**

Threshold current versus temperature



It can be found clearly that the threshold currents at 410 nm are much more stable with temperature and smaller than those at 390 nm.

Threshold current versus temperature



- Among the three laser structures, the one with an emission wavelength of 410 nm has the lowest threshold currents at all temperatures under study.
- The threshold currents are much more stable with temperature as emission wavelength increase.

- The simulation results indicate that the DQW laser structure with an emission wavelength of 385–410 nm has the lowest threshold current.
- The T_0 of the SQW laser structure increases as the emission wavelength increases.
- The DQW structure has the largest T_0 when the emission wavelength is larger than 405 nm, while the TQW structure possesses the largest T_0 when the emission wavelength is shorter than 405 nm.

- Y.-K. Kuo, *et al*., Opt. Communi. 231, 395 (2004).
- S. Nakamura, *et al*., Jpn. J. Appl. Phys. 37, L1020 (1998).
- T. Asano, *et al*., Appl. Phys. Lett. 80, 3497 (2002).
- C. Skierbiszewski, *et al*., Semicond. Sci. Technol. 20, 809 (2005).
- M. Kneissl, *et al*., Appl. Phys. Lett. 82, 2386 (2003).
- S. Nakamura, *et al*., Jpn. J. Appl. Phys. 40, L788 (2001).
- M. Kneissl, *et al*., Appl. Phys. Lett. 77, 1931 (2000).
- M. Kneissl, *et al*., Appl. Phys. Lett. 75, 581 (1999).
- C. Sasaoka, *et al*., Phys. Stat. Sol. (a) 203, 1824 (2006).
- T. Świetlik, *et al*., Appl. Phys. Lett. 88, 071121 (2006).
- S. Nakamura, MRS Internet J. Nitride Semicond. 2, 5 (1997).