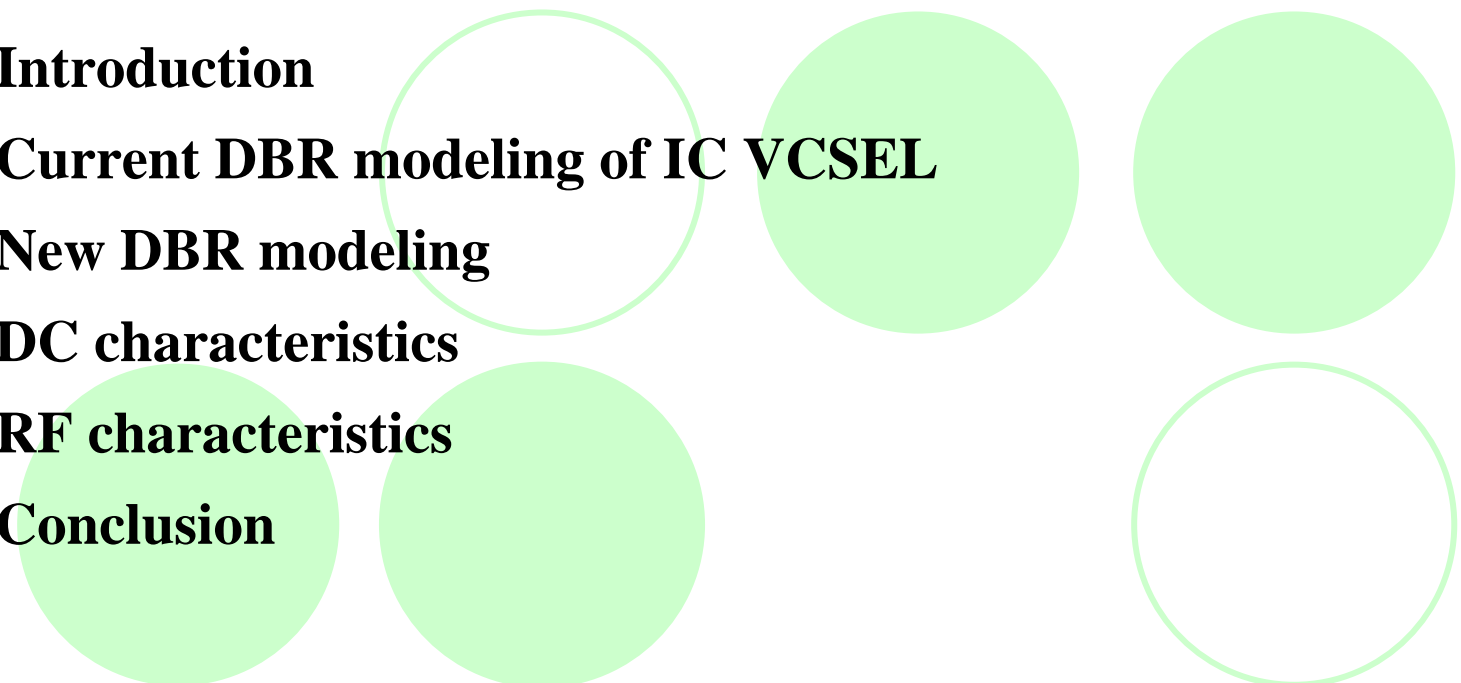




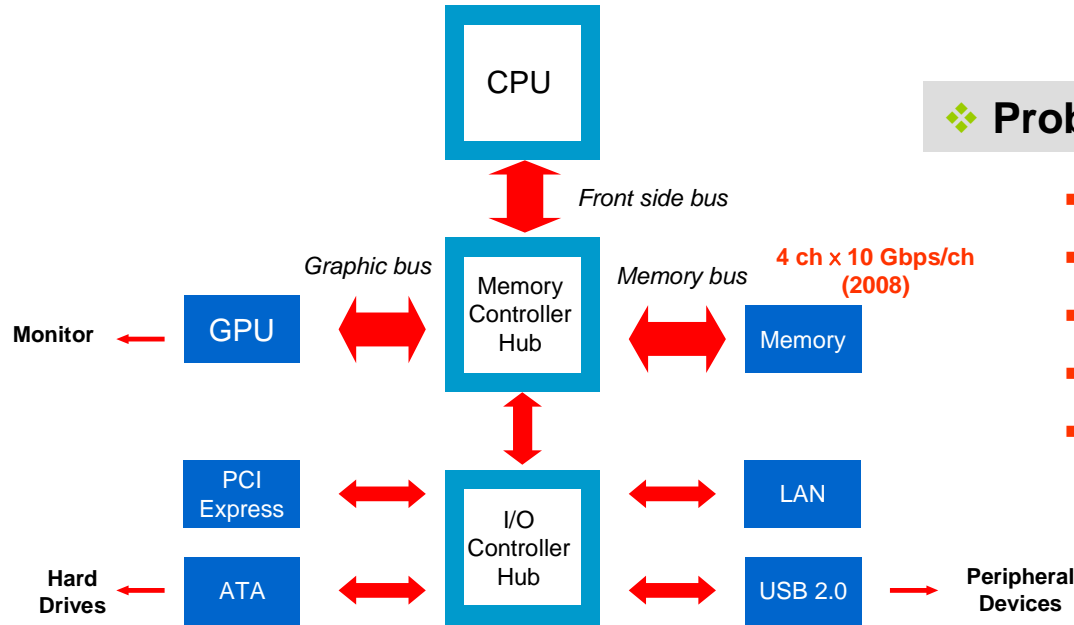
# DBR modeling of intra-cavity contacted VCSEL simulation

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Dept. of Information and Communications  
Gwangju Institute of Science and Technology

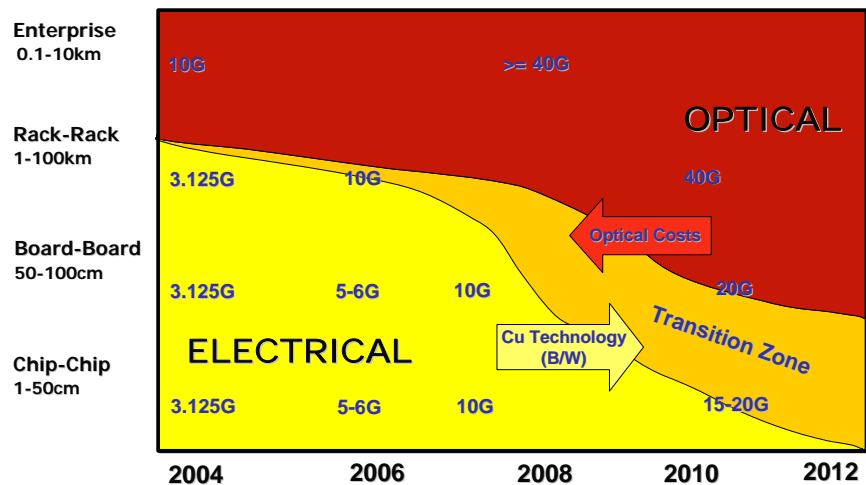
- 1. Introduction**
  - 2. Current DBR modeling of IC VCSEL**
  - 3. New DBR modeling**
  - 4. DC characteristics**
  - 5. RF characteristics**
  - 6. Conclusion**
- 
- The slide features six decorative green circles arranged in a 2x3 grid. The top row contains three circles: the first is a thin outline, the second and third are solid. The bottom row contains three circles: the first and second are solid, and the third is a thin outline.

# Optical interconnects in the computing platform



## Problems in the electrical interconnects

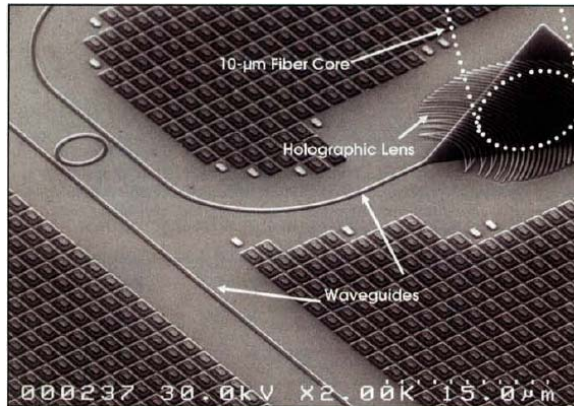
- Bandwidth : 10 ~15 Gbps (FR4 PCB)
- Power problem
- Interconnect density
- Limited reach
- EMI problem



Target cost (optical interconnect)  
: < \$1/Gbps

# Monolithic integration of VCSELs and RCEPDs

- ❖ Si light source + Si modulator + Si photodetector + Si electrical circuits

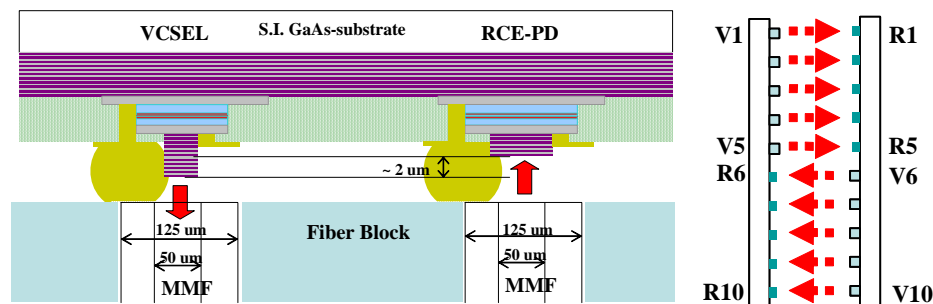


- ✓ Si laser technology is immature.
- ✓ Luxtera demonstrated 10 Gb/s transceivers on Si platform. (1545 nm InP VCSEL)

C. Gunn, *Photonics Spectra*, p. 62, Mar. 2006

- ❖ Integrated VCSEL and RCEPD + Si electrical circuits

- ✓ III-V light source + III-V photodetector on Si-platform



- VCSELs have already been the choice for the light source of short-distance optical interconnects.
- Reduced fabrication cost
- Reduced packaging cost (one alignment with optical waveguide instead of two)

# Design issues

## ❖ VCSEL

- Lower self-heating  
**Relatively high differential resistance (on going)**
- High speed for 10 Gb/s  
**6.5 GHz at 6 mA**  
**V. Lyask, APL, 87, 231118 (2006)**
- High speed at lower currents  
**Epi-design, Parasitic design (on going)**
- Ease of coupling with optical waveguide  
**C. Chang, IEEE PTL, to be published**
- Single-mode characteristics  
**Optical mode design using FEM/FDTD (on going)**

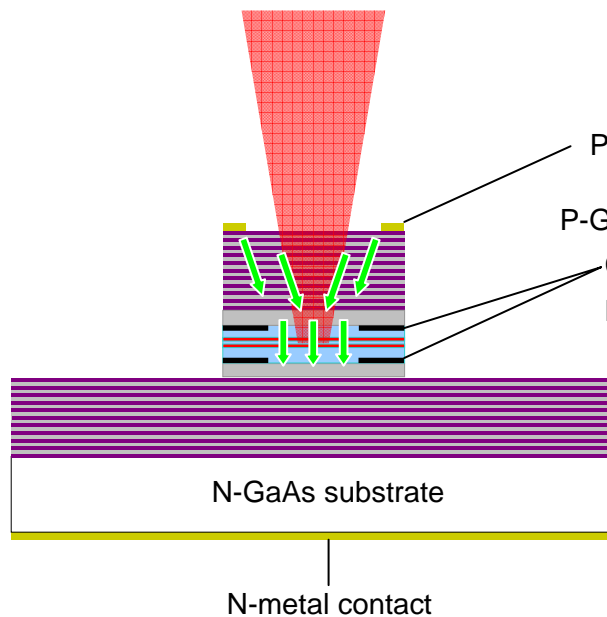
- Optimization of epi structure for integration

## ❖ RCEPD

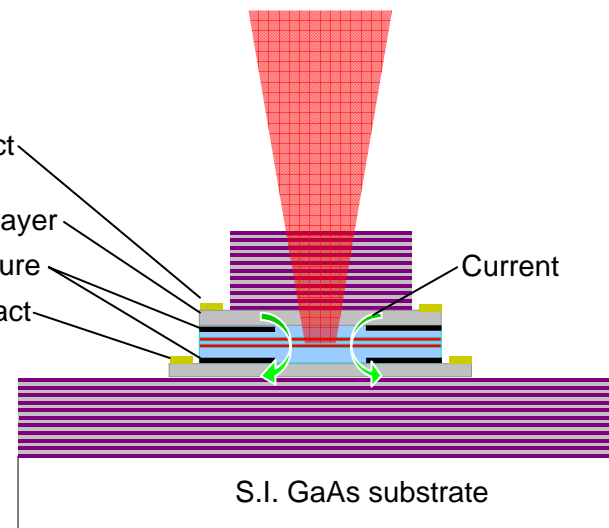
- Temperature sensitivity of RCEPD  
**I. Chung, IEEE PTL, v. 18, p. 46 (2006)**
- Spectral bandwidth  
**940-nm InGaAs/GaAs QWs**
- High speed for 10 Gb/s  
**9 GHz f<sub>3dB</sub>**  
**I. Chung, SPIE proc., 6352-62 (2006)**

# Intra-cavity contacted VCSEL

## ❖ Extra-cavity contacted VCSEL

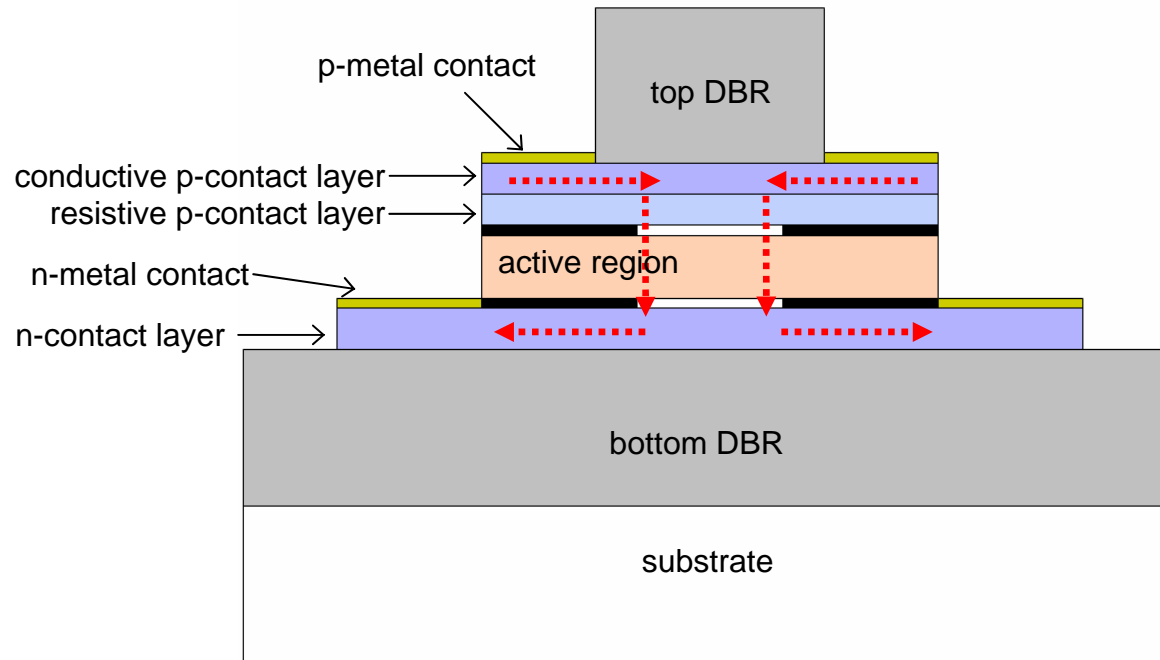


## ❖ Intra-cavity contacted VCSEL

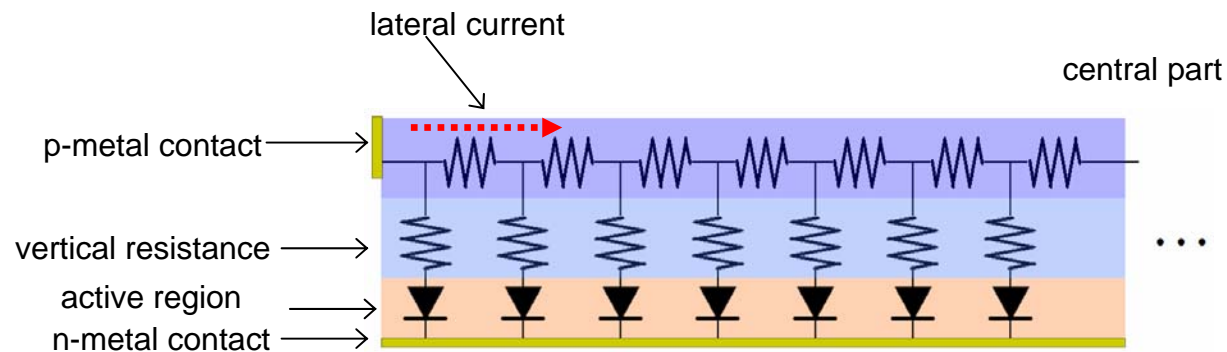


- IC VCSELs are more adequate for high speed applications
- In EC VCSELs, current flows uniformly into the active region.
- In IC VCSELs, current tends to shunt around the rim of oxide aperture at high driving currents. This is called as current crowding problem.

# Current crowding in IC VCSELs



- Current crowding can be relaxed by inserting vertical resistance between the p-contact and active region.



- ❖ Reducing the doping concentration of p-layer

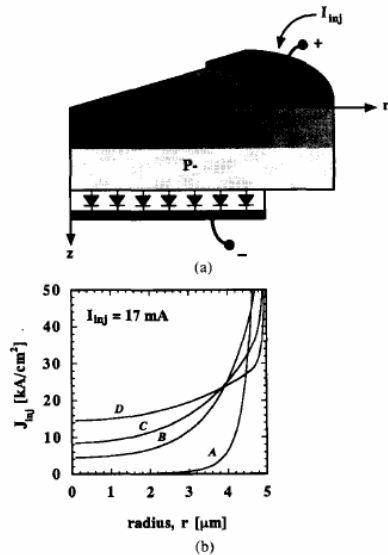
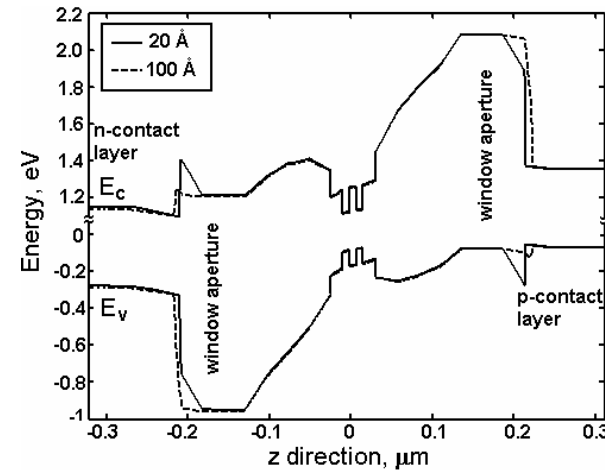


Fig. 12. (a) Schematic of the 2-D finite element model used to calculate the injected current profiles. Because the electron mobilities are so much greater, the *n* contacting layer has been modeled as a ground plane. (b) Plot demonstrating the current leveling effect of the resistive layer. Curve *A* is for no leveling layer. Curves *B*, *C*, and *D* are for progressively more resistive current leveling layers.

J. W. Scott, IEEE JQE, **29**, 1295 (1993)

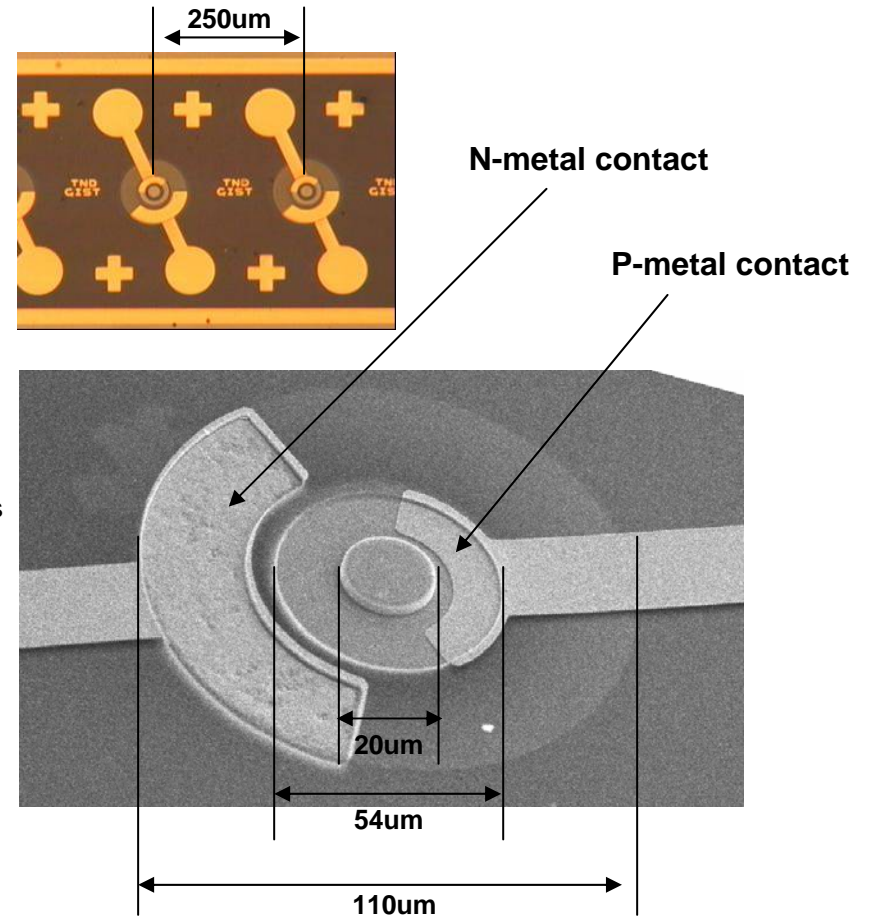
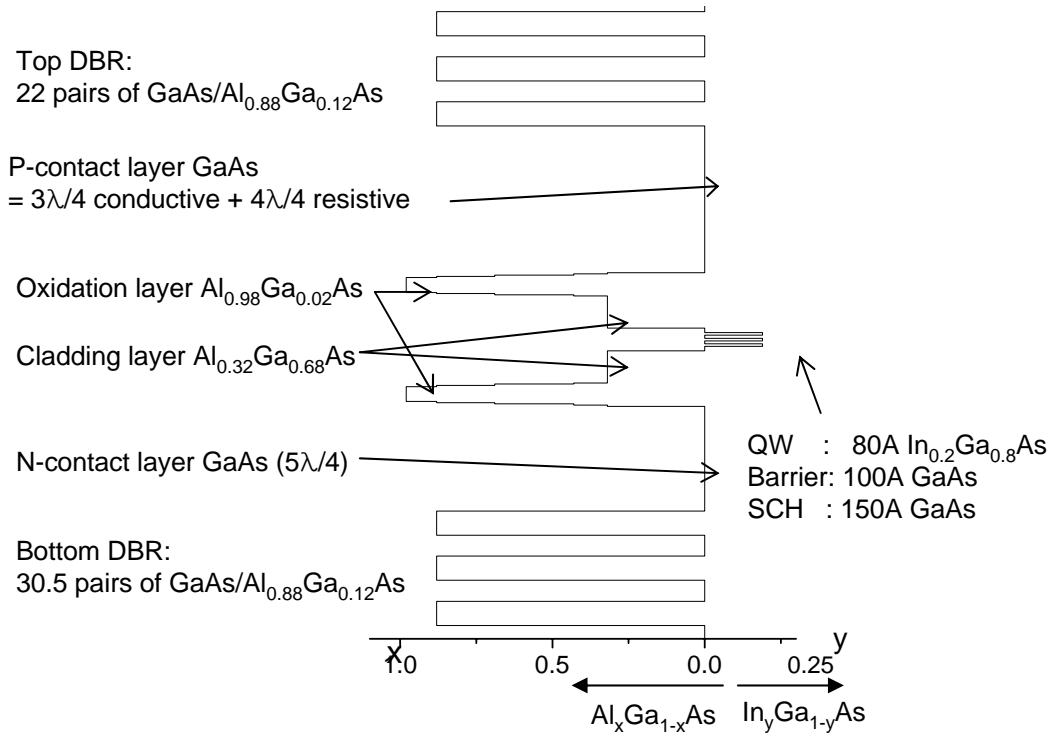
- ❖ Reducing the thickness of grading layers



V. V. Lyask, APL, **87**, 231118 (2006)

- Precise calculation of lateral current is important!

# Device structure





# VCSEL simulation

## Optical part

- Longitudinal mode
- Lateral/transverse mode

▪ Relatively fast

## Electrical part

- Gain calculation
- Index calculation
- Carrier transport

▪ Relatively slow

## Thermal part

- Heat transport

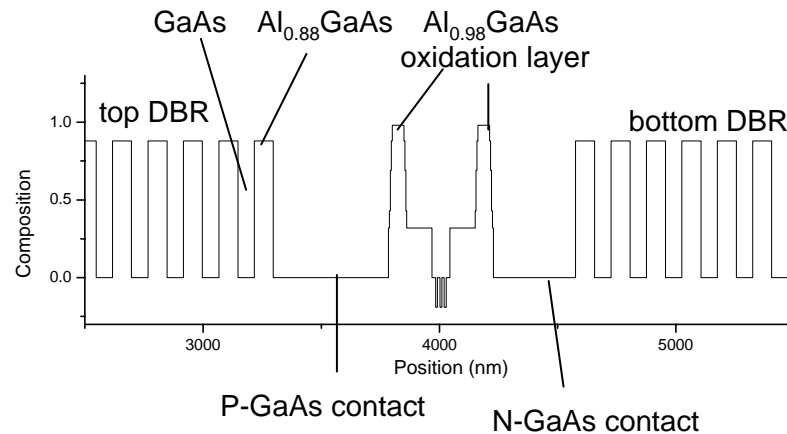
▪ Relatively fast



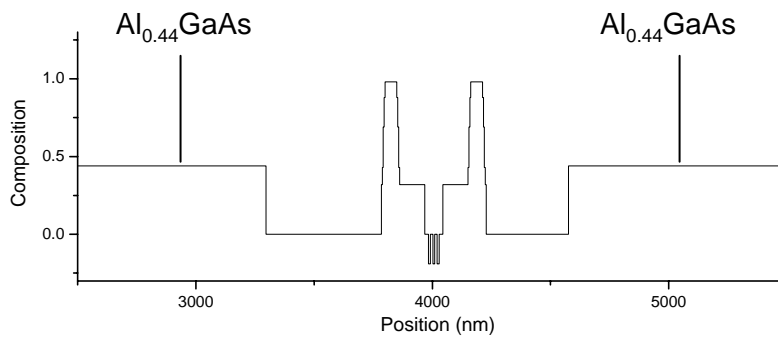
▪ Averaged DBR approx.

# Fully-averaged DBR approx.

❖ For optical mode calculation

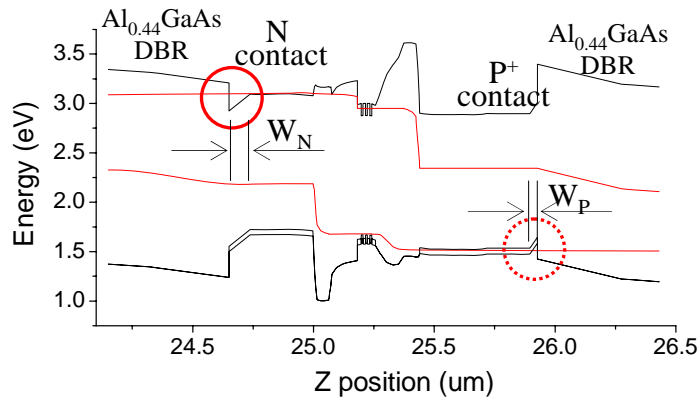


❖ For electrical calculation (band-calculation, carrier-transport)

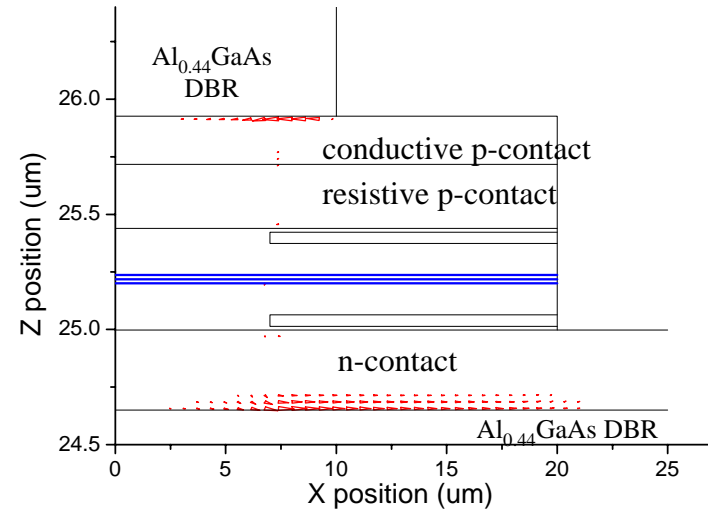


# Fully-averaged DBR approx.

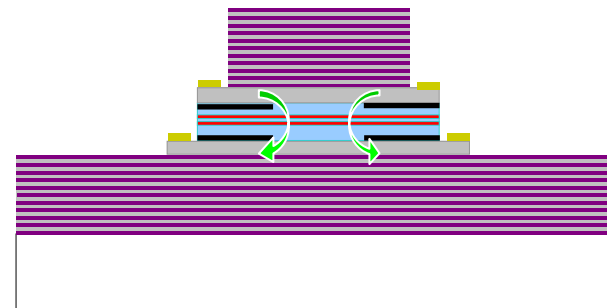
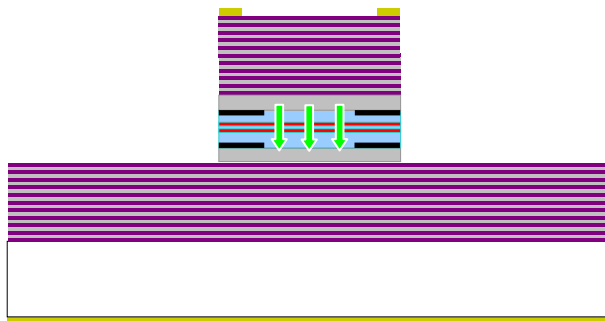
## ❖ Exaggerated energy bending



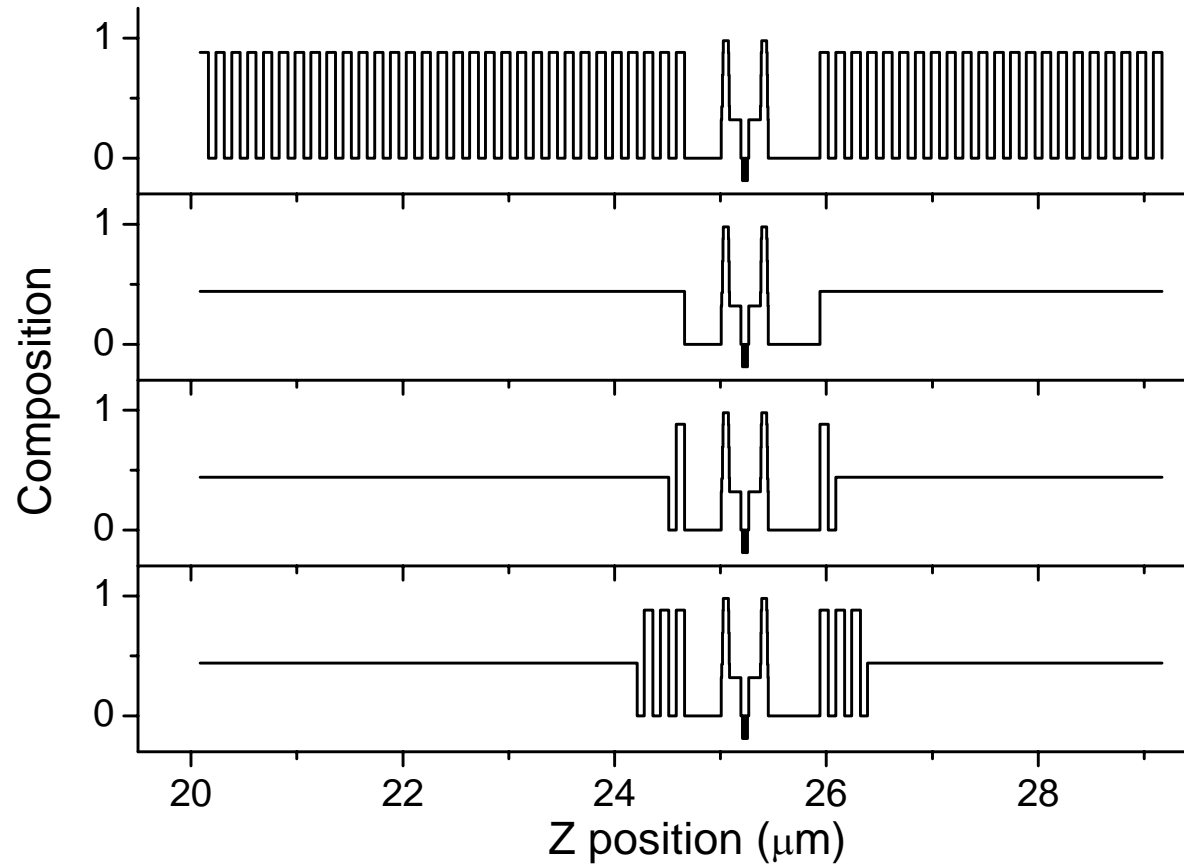
## ❖ Unrealistic lateral currents



- Lateral current is less important in EC VCSELs
- Fully-averaged DBRs effectively approximate EC VCSELs but not IC VCSELs



# Partially-averaged DBR approx.



■ Not-averaged

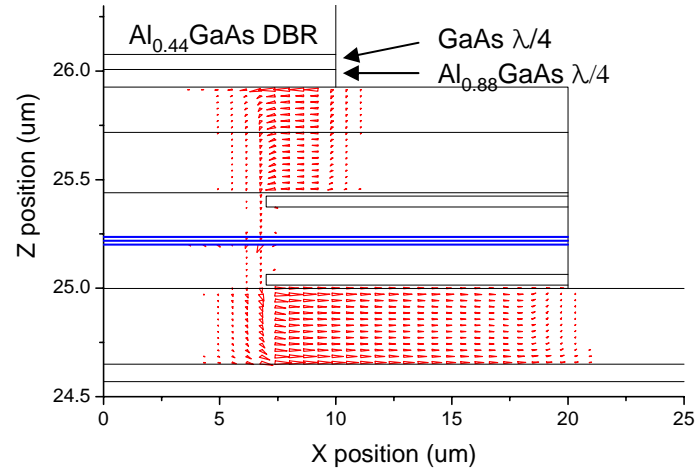
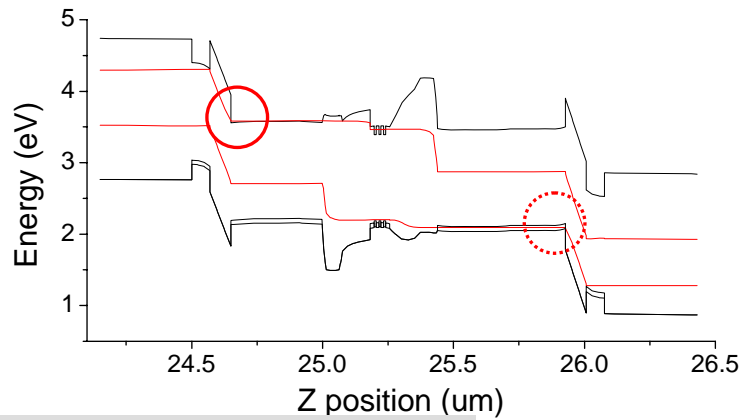
■ Fully-averaged (FA)

■ Partially-averaged 1 (PA1)

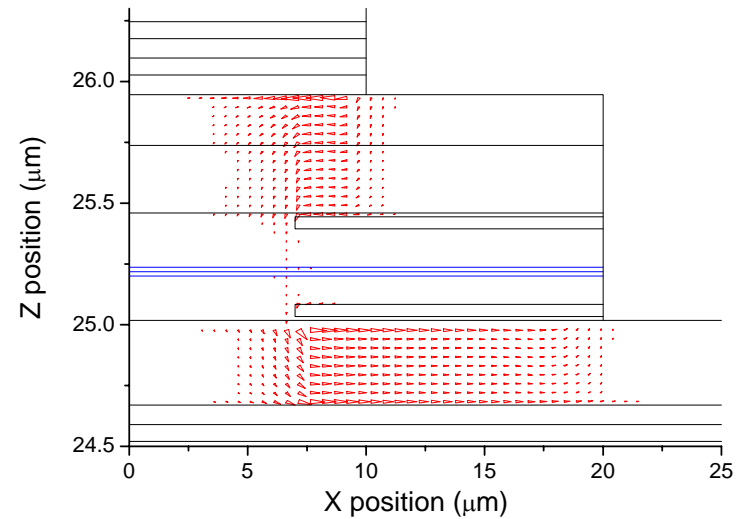
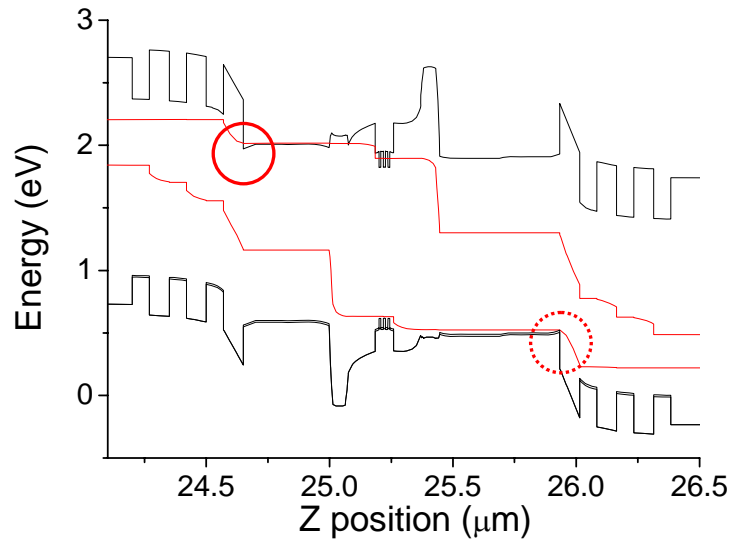
■ Partially-averaged 3 (PA3)

# Partially-averaged DBR approx.

## ❖ Partially-averaged 1

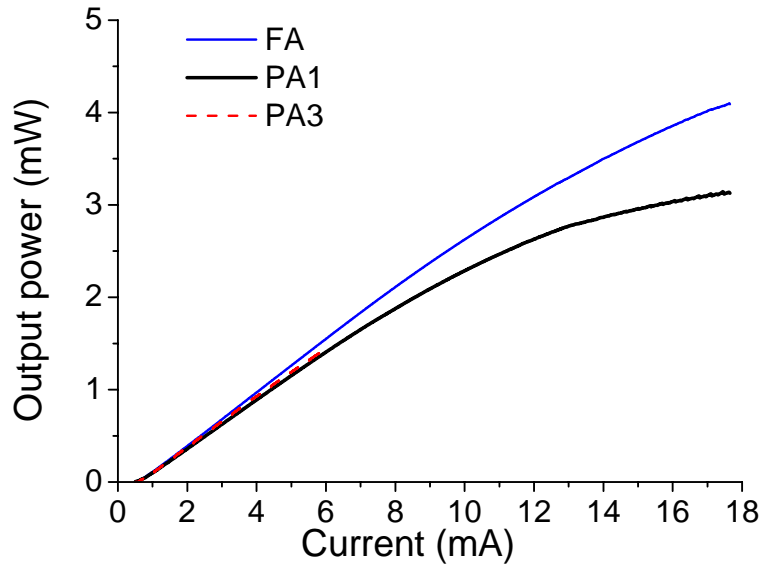


## ❖ Partially-averaged 3



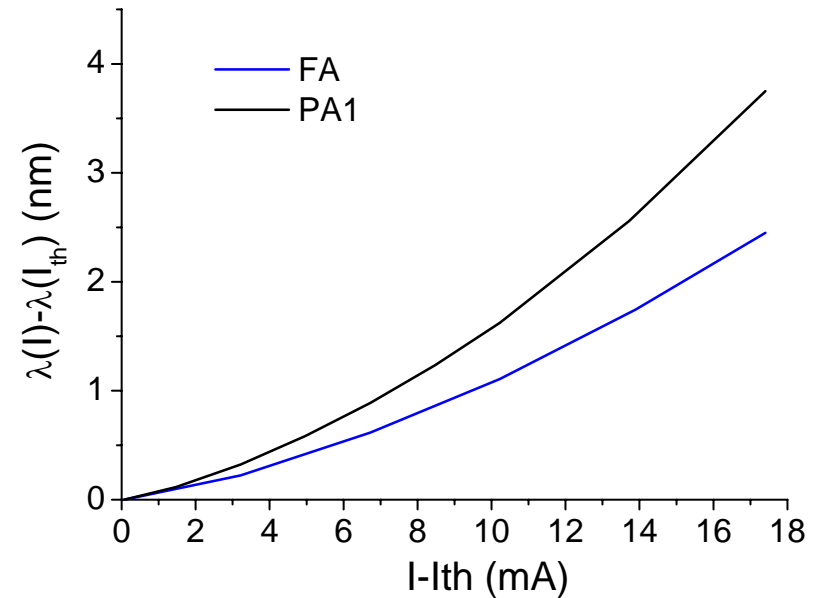
# DC characteristics

## ❖ Current–Output power



- In fully-averaged case, roll-over is less severe at higher currents because of unrealistic relaxation of current crowding.

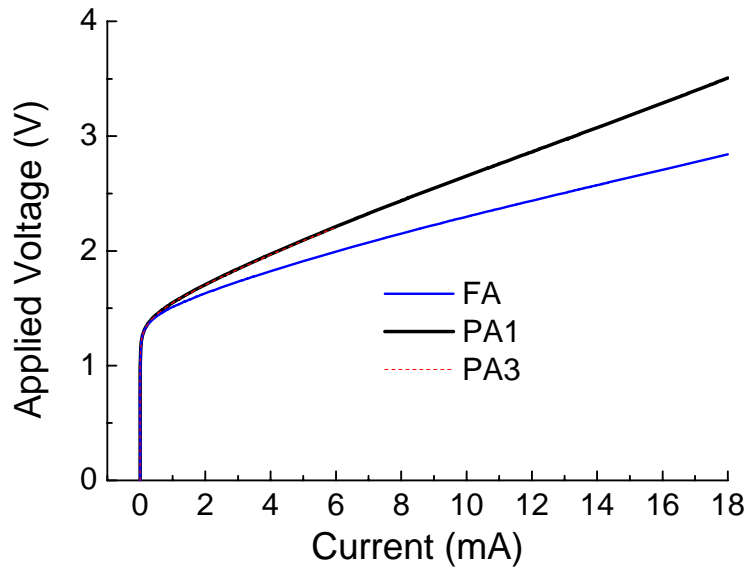
## ❖ Wavelength Shift



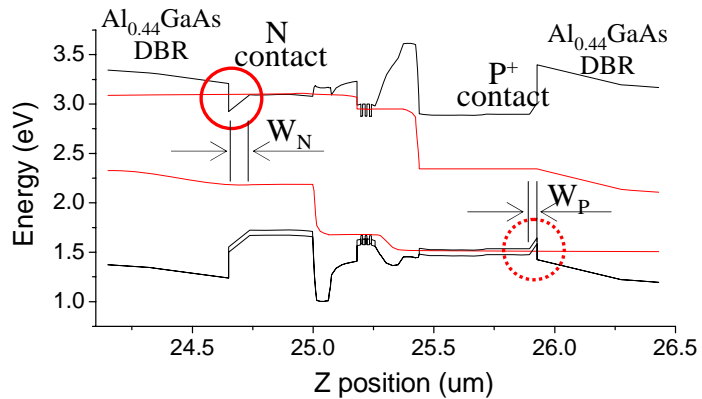
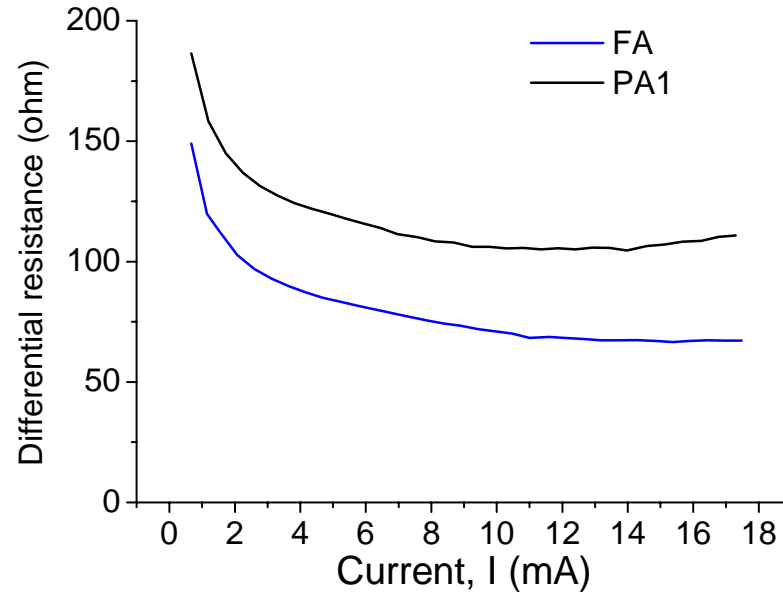
- In fully-averaged case, cavity-mode wavelength red-shifts less than the realistic partially-averaged case because of smaller heat generation.

# Resistance

## I-V curve

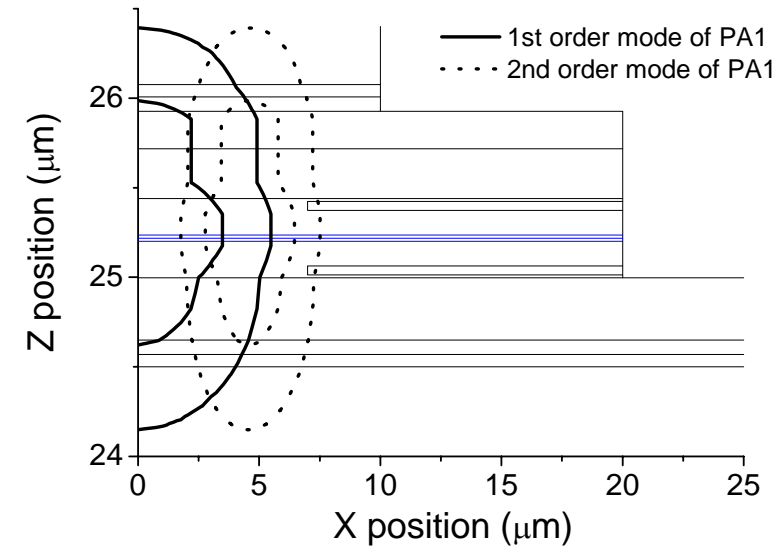
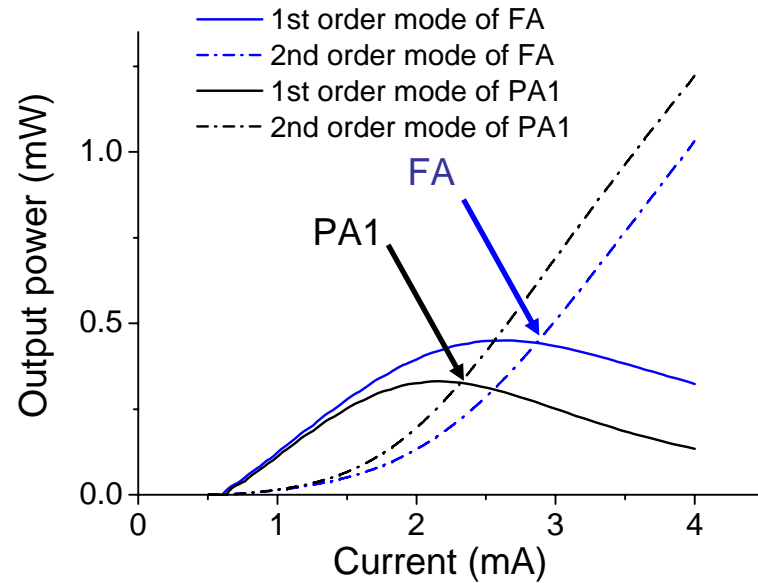


## Differential resistance



- The lateral current channels of the fully-averaged case make the differential resistance unrealistically small.

# Higher mode excitation



- In the fully-averaged case, the higher mode grow slowly because of the relaxation of current crowding.

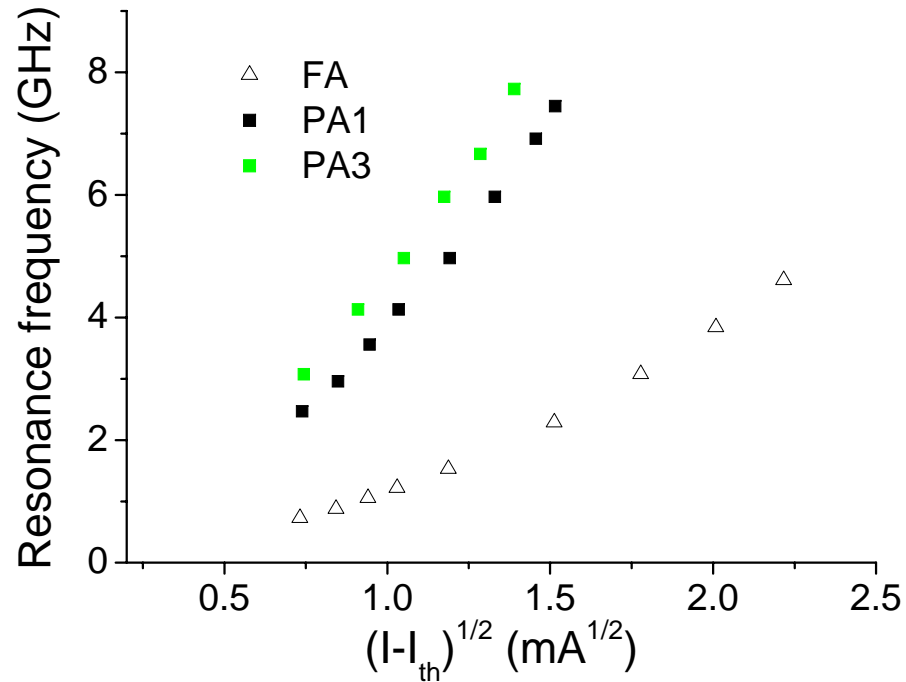
# DC characteristics summary

TABLE I  
ELECTRICALLY-AVERAGED MODELING VERSUS MODIFIED MODELING

	Electrically-averaged modeling	Modified modeling
Output	5.3mW	4.0mW
Joule heat	21.5mW	32.9mW
Recombination heat	7.0mW	9.7mW
Highest temperature	56.7°C	71.7°C
Threshold current	0.69mA	0.68mA

\* All the quantities except for threshold currents are measured at an injection current of  $I=22\text{mA}$ .

# RF characteristics

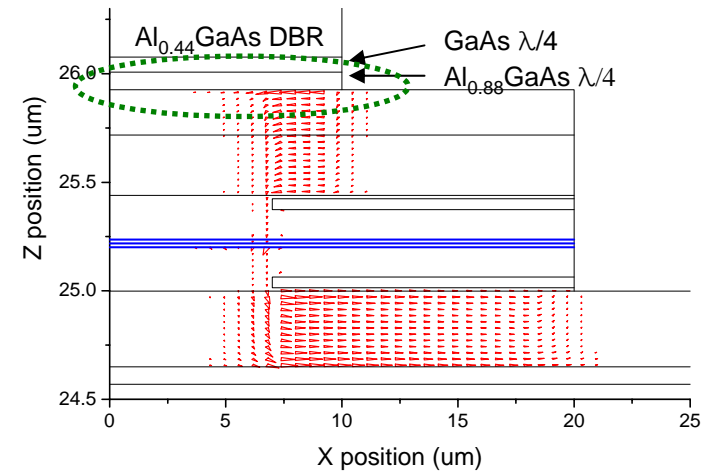
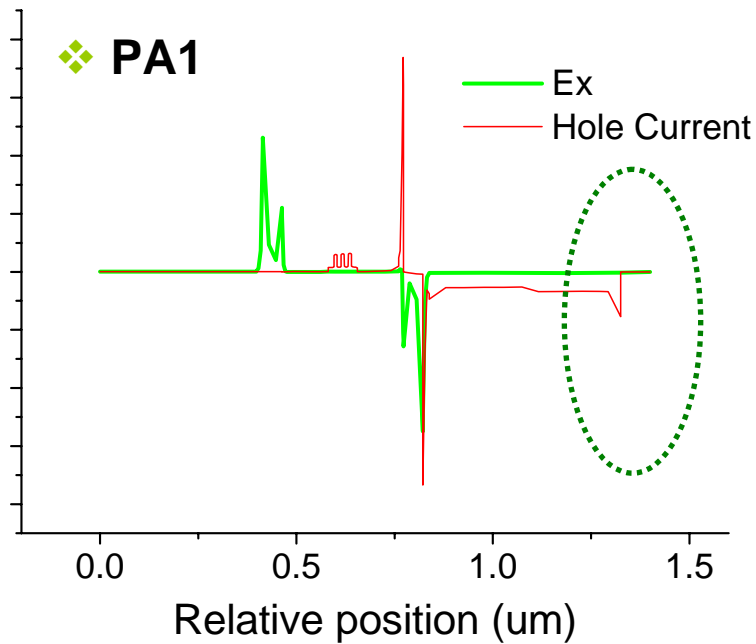
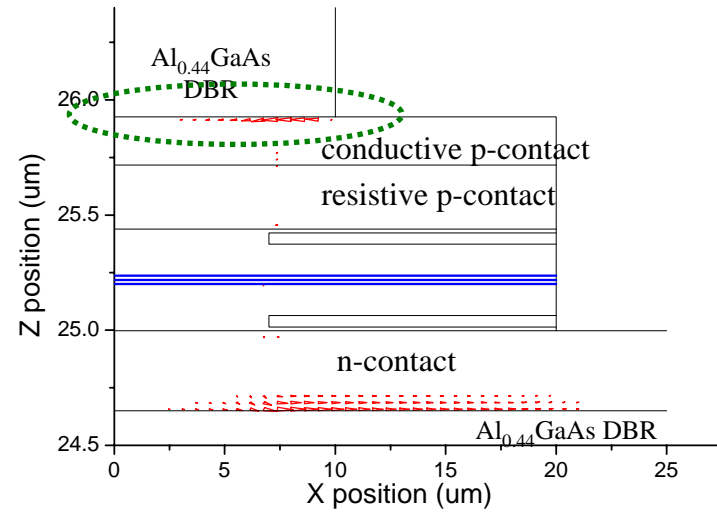
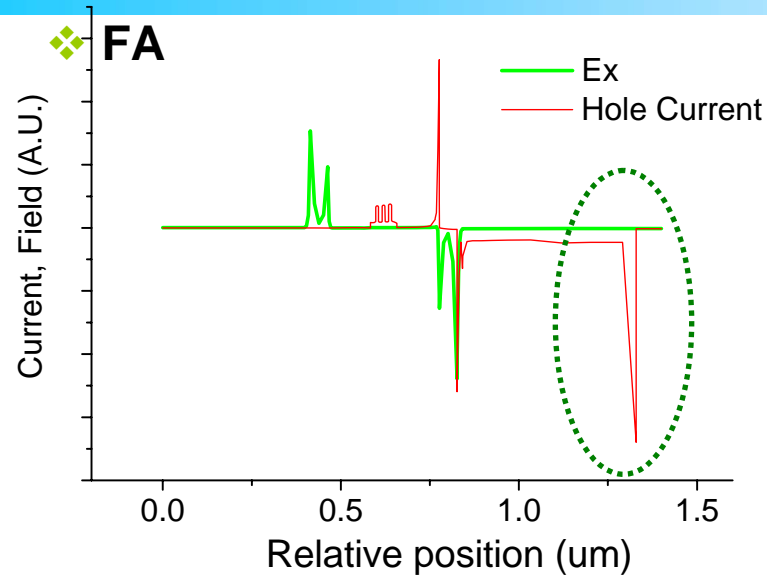


$$\omega_R = \sqrt{\frac{v_g a}{qV_p} \eta_i (I - I_{th})}$$

- Because of slow lateral diffusion current (unrealistic), the response of the fully-averaged (FA) case is much slower than the partially-averaged (PA) cases.



# Transport effect on bandwidth





- Electrically fully-averaged DBR approximation misleads to unrealistic lateral current channels.
- This lateral current relaxes the current crowding problem near the current aperture.
  - ✓ It overestimates output power.
  - ✓ It underestimates the amount of self-heating.
  - ✓ It exaggerates single mode characteristics.
  - ✓ It underestimates the 3-dB bandwidth.
- Partially-averaged DBR approximation effectively solve these problems.