DBR modeling of intra-cavity contacted VCSEL simulation

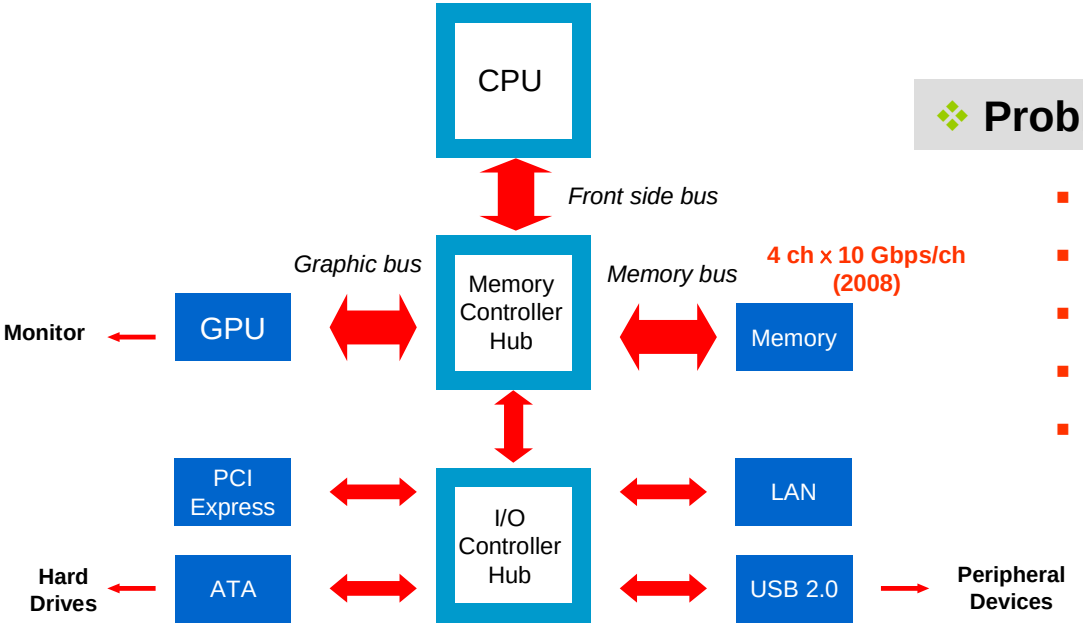
Il-Sug Chung and Yong Tak Lee

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

Outline

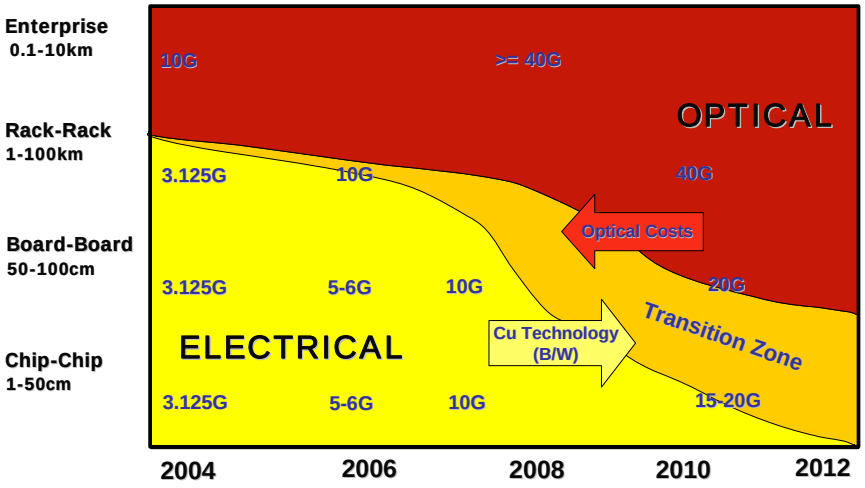
1. Introduction
2. Current DBR modeling of IC VCSEL
3. New DBR modeling
4. DC characteristics
5. RF characteristics
6. Conclusion

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

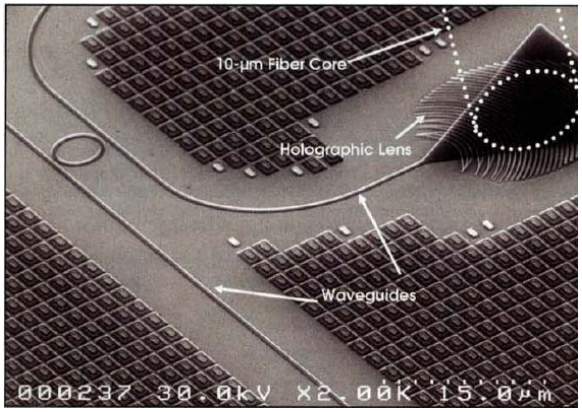


Target cost (optical interconnect)
: < $1/Gbps

J. Bautista, SPIE v.5729, 1 (2005)

Monolithic integration of VCSELs and RCEPDs

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



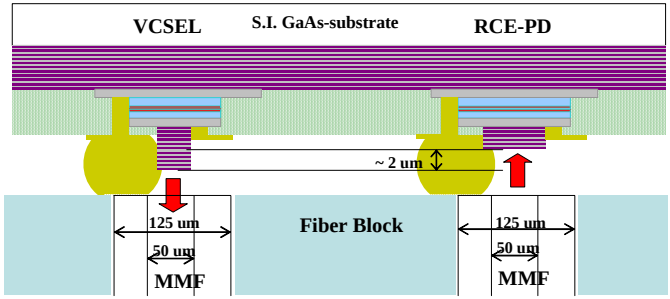
✓ Si laser technology is immature.

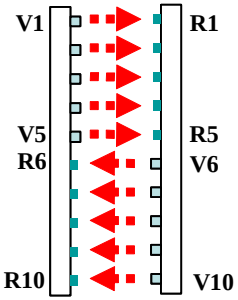
✓ Luxtera demonstrated 10 Gb/s transceivers on Si platform.
(1545 nm InP VCSEL)

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)

RCEPD

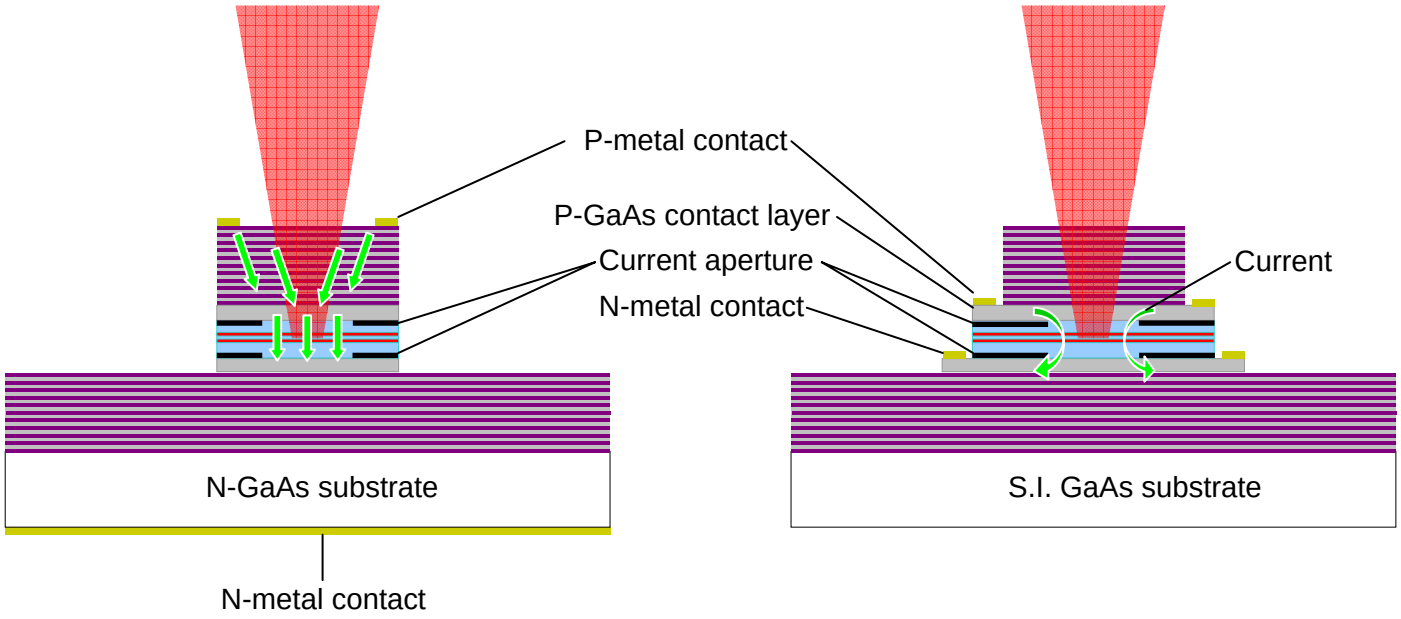
- Temperature sensitivity of RCEPD
  I. Chung, IEEE PTL, v. 18, p. 46 (2006)
- Spectral bandwidth
  940-nm InGaAs/GaAs QWs
- High speed for 10 Gb/s
  9 GHz f_3dB
  I. Chung, SPIE proc., 6352-62 (2006)

- Optimization of epi structure for integration

Intra-cavity contacted VCSEL

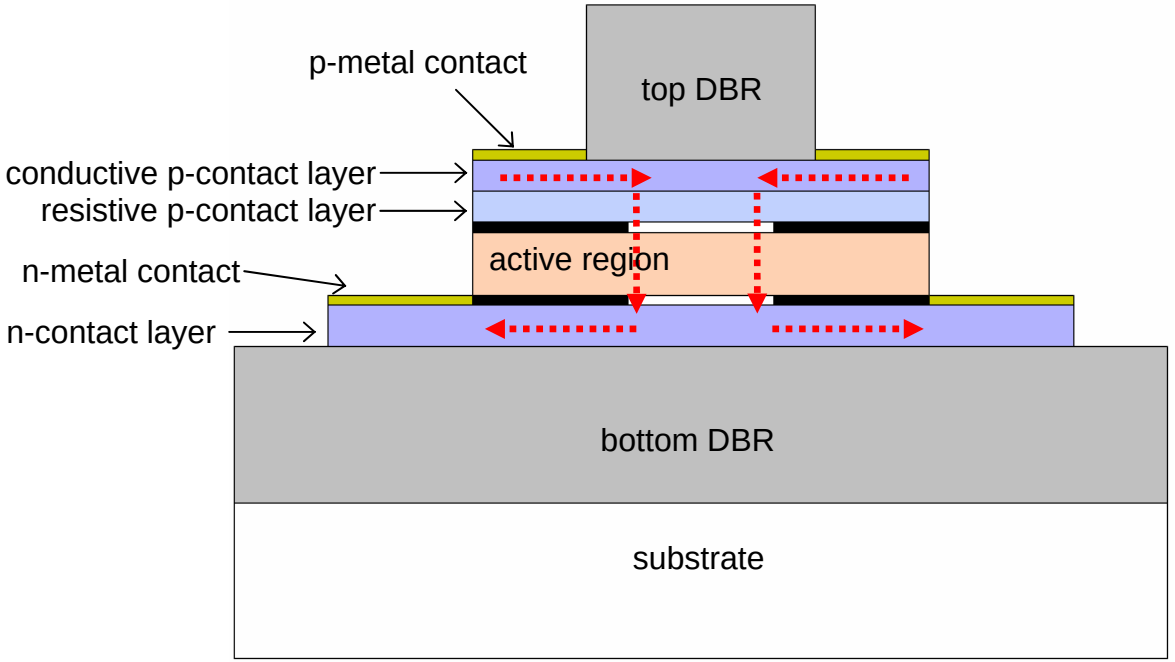
❖ **Extra-cavity contacted VCSEL**

❖ **Intra-cavity contacted VCSEL**

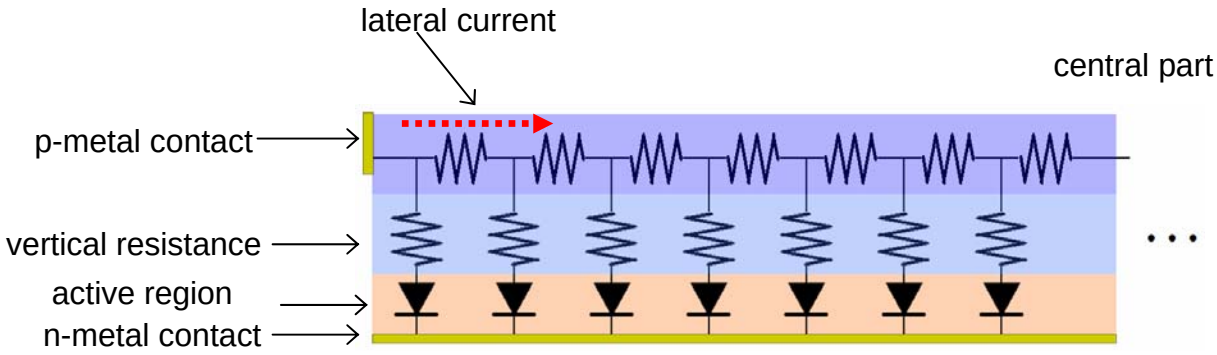


- IC VCSELs are more adequate for high speed applications
- In EC VCSELs, current flows uniformly into the active region.
- In IC VCSELs, current tends to shunt around the rim of oxide aperture at high driving currents. This is called as current crowding problem.

Current crowding in IC VCSELs



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



Relaxing current crowding

❖ Reducing the doping concentration of p- layer

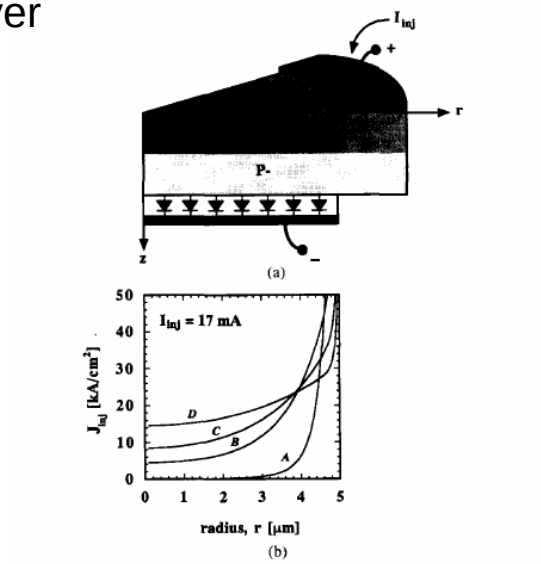
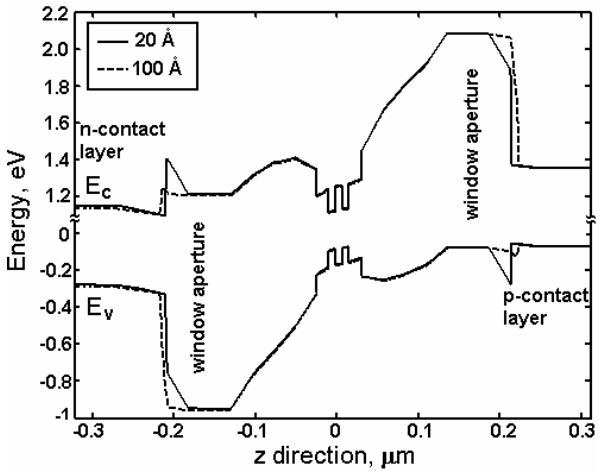


Fig. 12. (a) Schematic of the 2-D finite element model used to calculate the injected current profiles. Because the electron mobilities are so much greater, the *n* contacting layer has been modeled as a ground plane. (b) Plot demonstrating the current leveling effect of the resistive layer. Curve *A* 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)

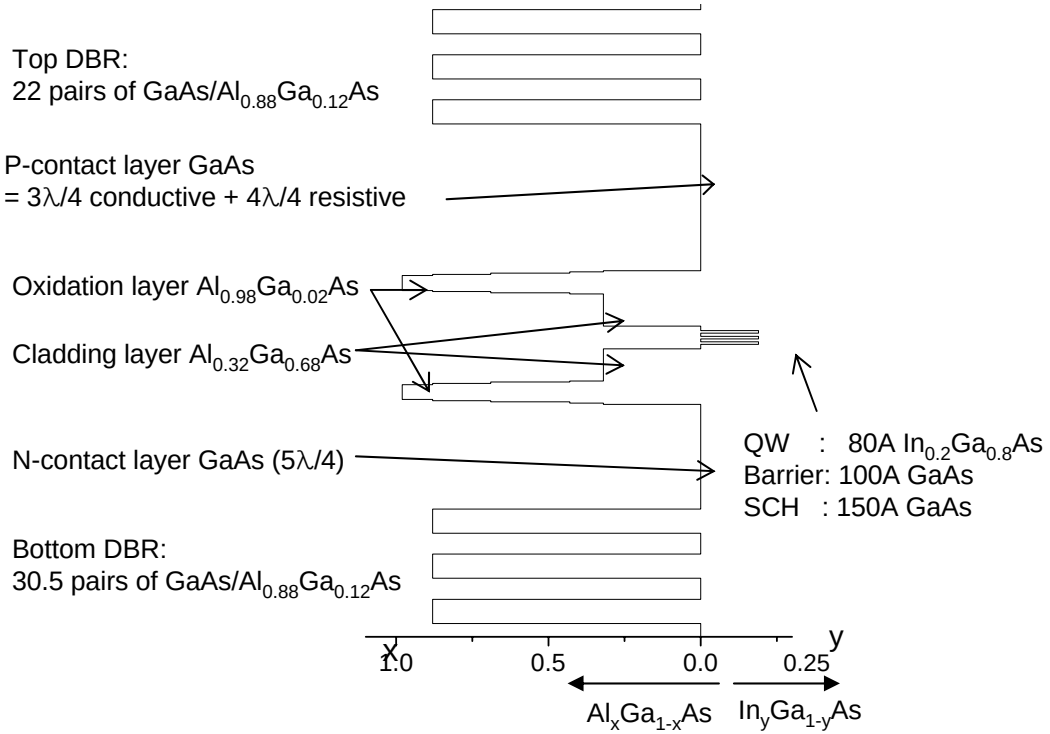
❖ Reducing the thickness of grading layers

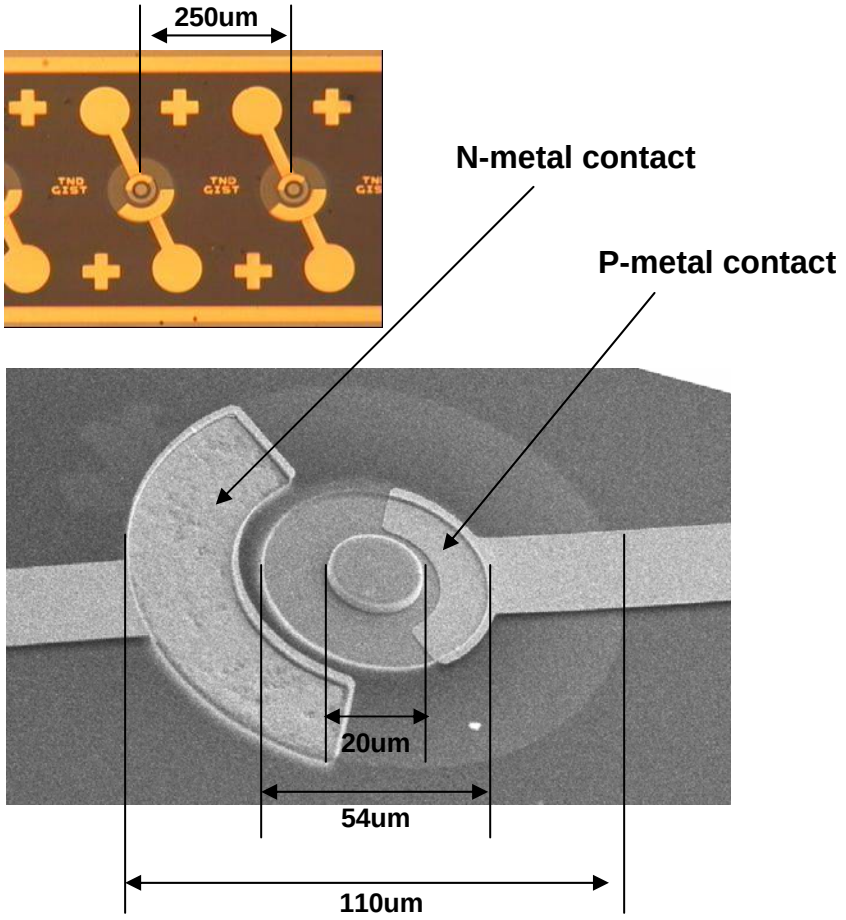


V. V. Lyask, APL, **87**, 231118 (2006)

- 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

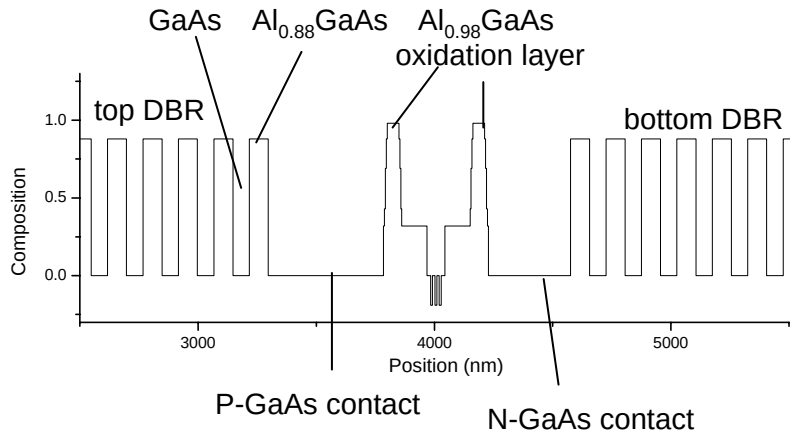
- Heat transport

- Relatively fast

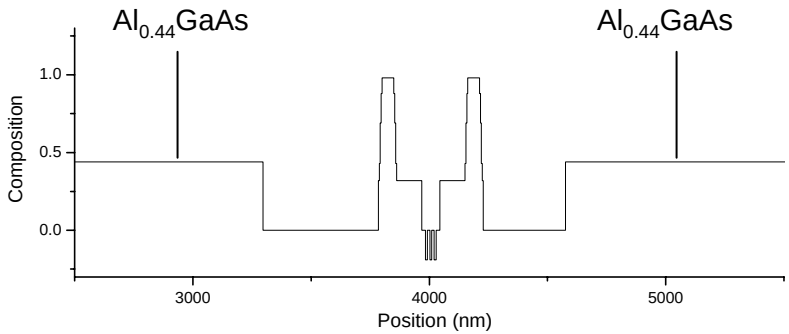
- Averaged DBR approx.

Fully-averaged DBR approx.

- For optical mode calculation

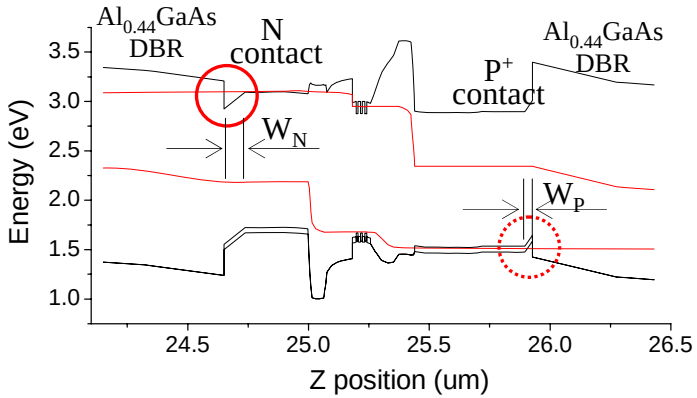


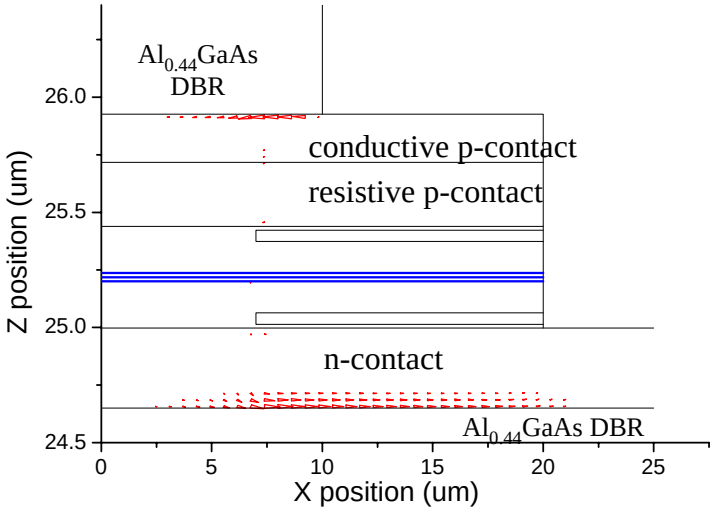
- For electrical calculation (band-calculation, carrier-transport)



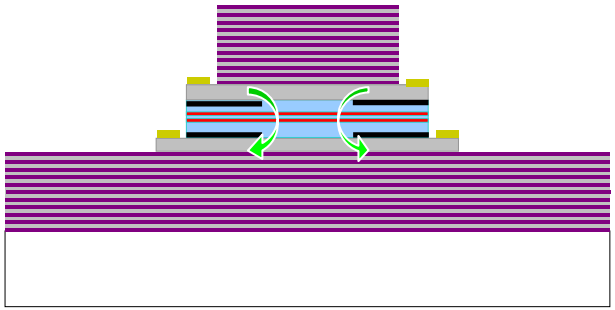
Fully-averaged DBR approx.

- Exaggerated energy bending
- Unrealistic lateral currents

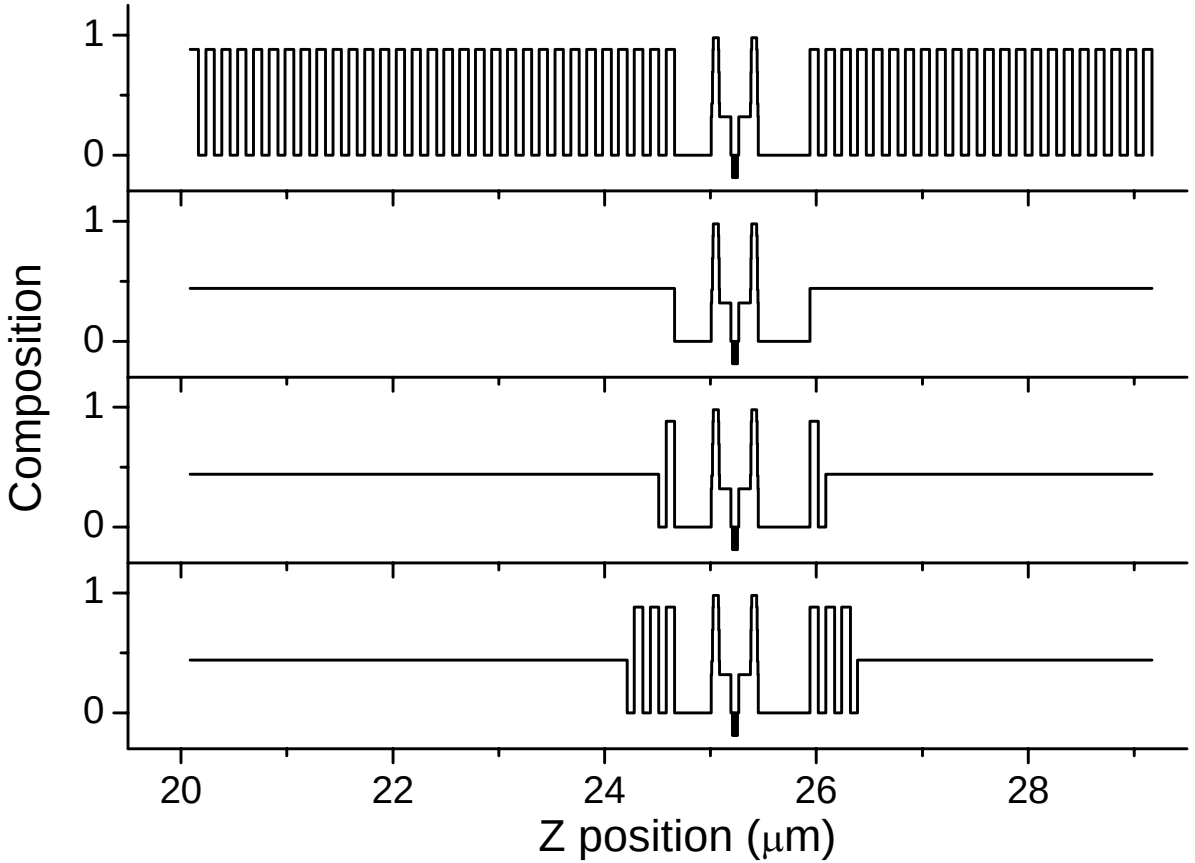




- Lateral current is less important in EC VCSELs
- Fully-averaged DBRs effectively approximate EC VCSELs but not IC VCSELs



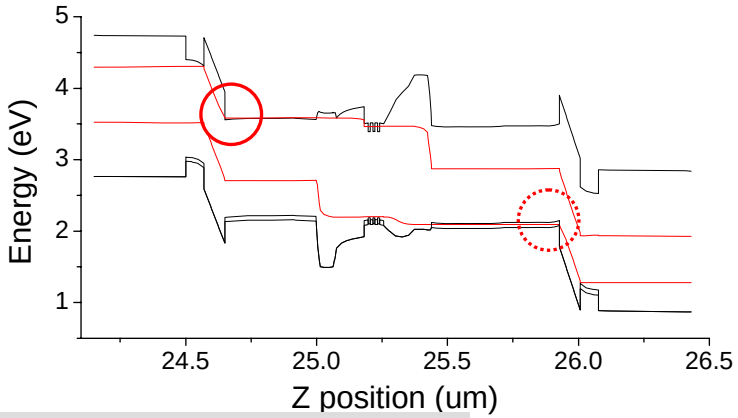
Partially-averaged DBR approx.

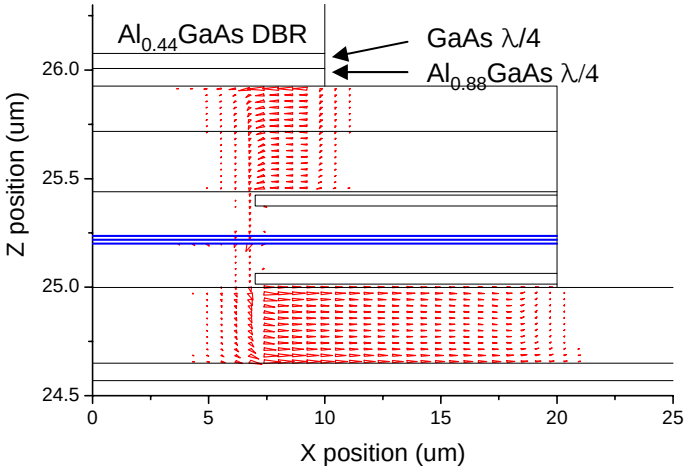


- Not-averaged
- Fully-averaged (FA)
- Partially-averaged 1 (PA1)
- Partially-averaged 3 (PA3)

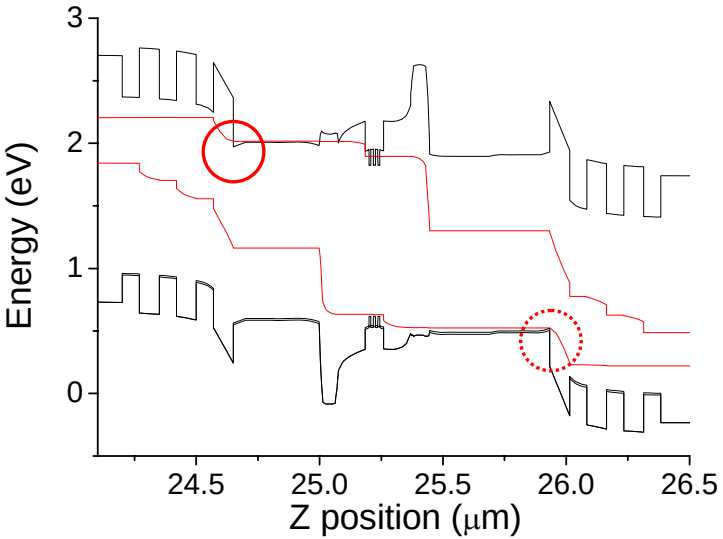
Partially-averaged DBR approx.

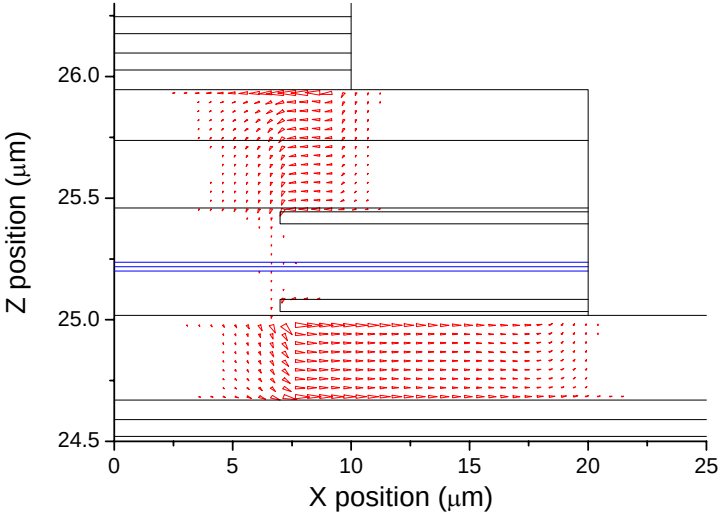
- Partially-averaged 1





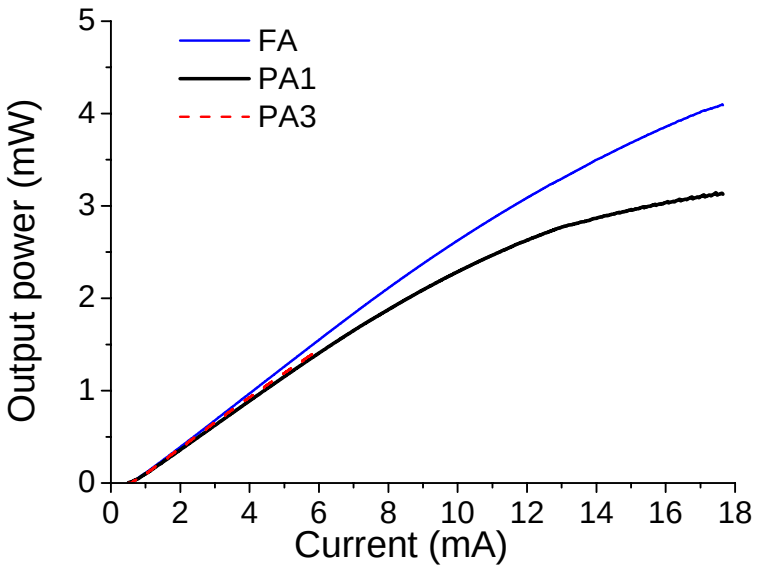
- Partially-averaged 3





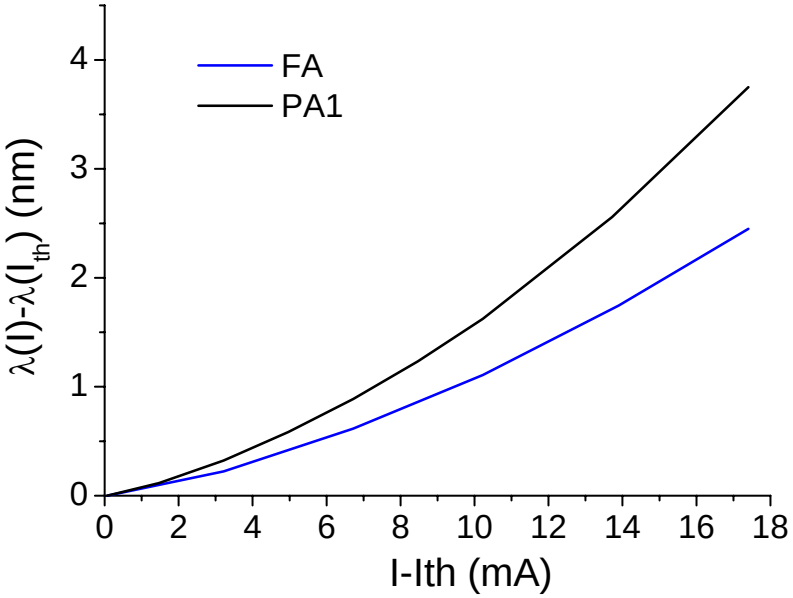
DC characteristics

❖ Current–Output power



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

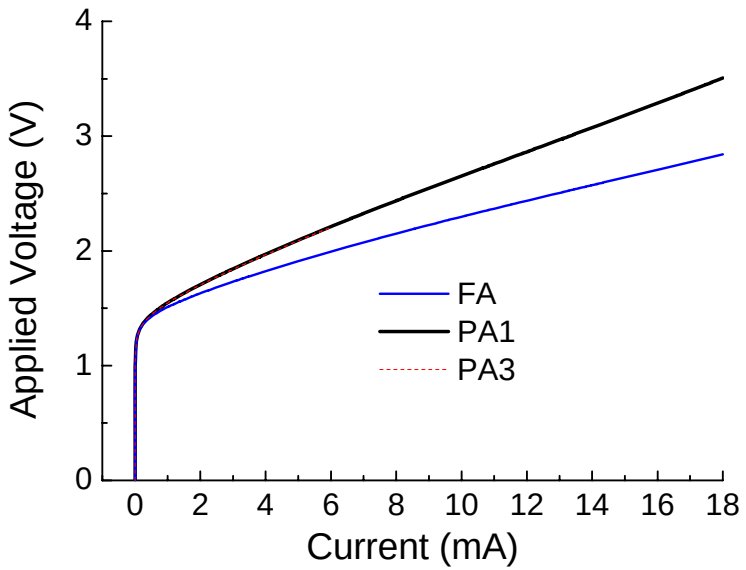
❖ Wavelength Shift

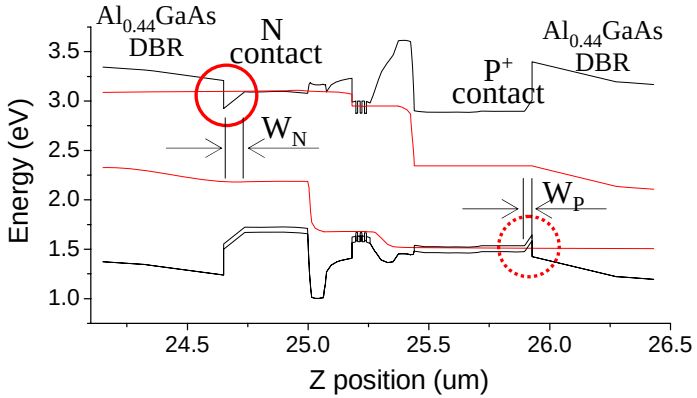


- In fully-averaged case, cavity-mode wavelength red-shifts less than the realistic partially-averaged case because of smaller heat generation.

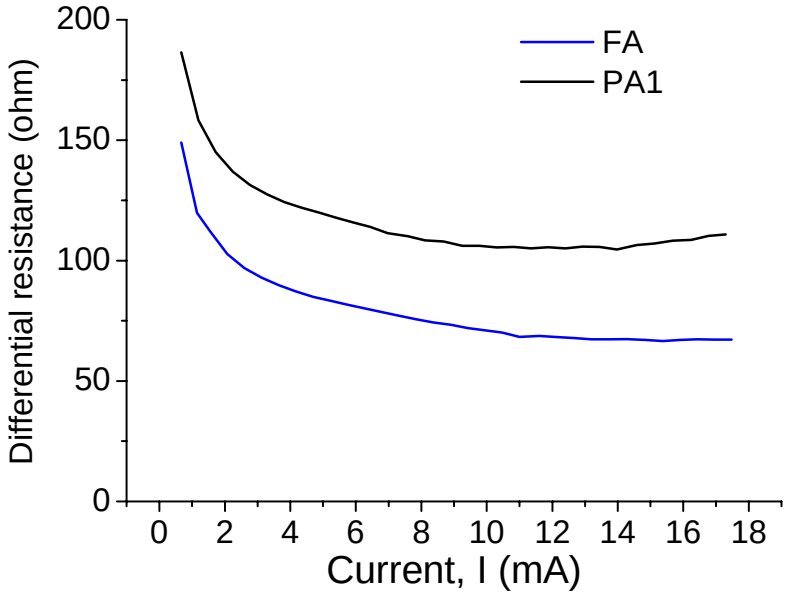
Resistance

❖ I-V curve



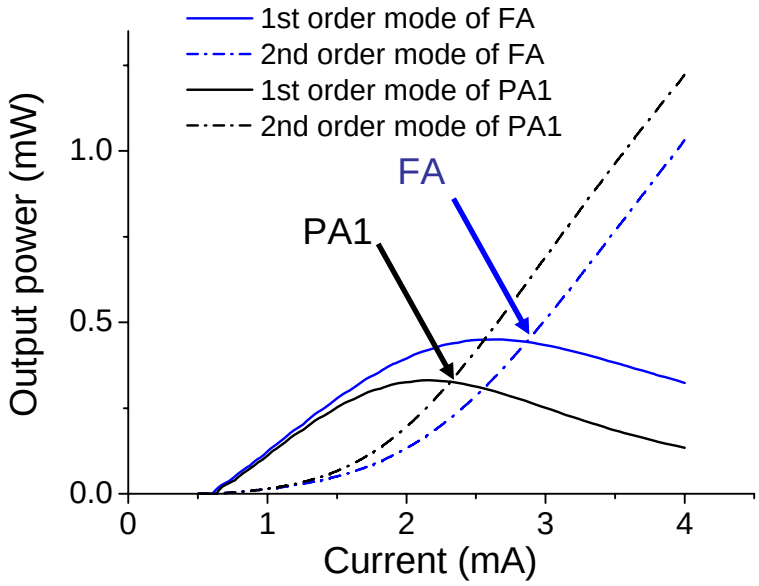


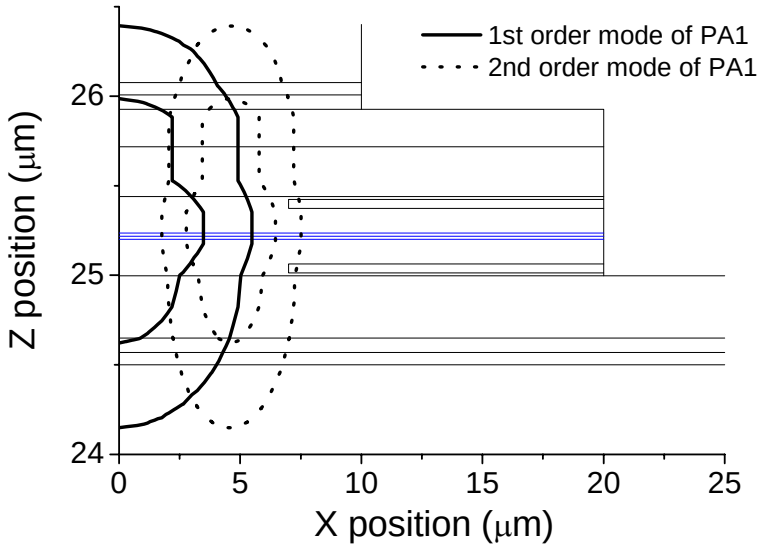
❖ Differential resistance



- 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.

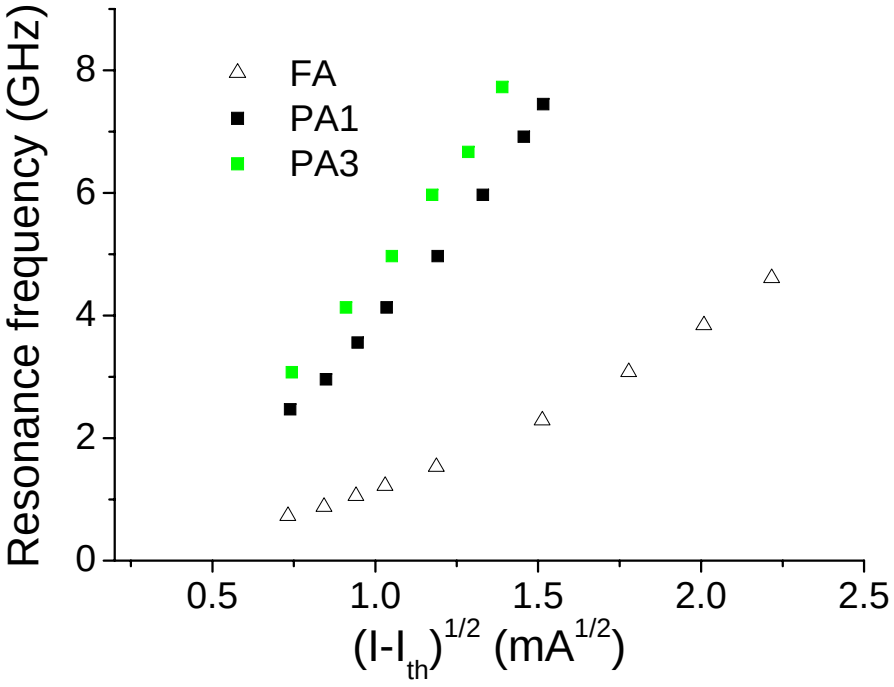
DC characteristics summary

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=22mA.

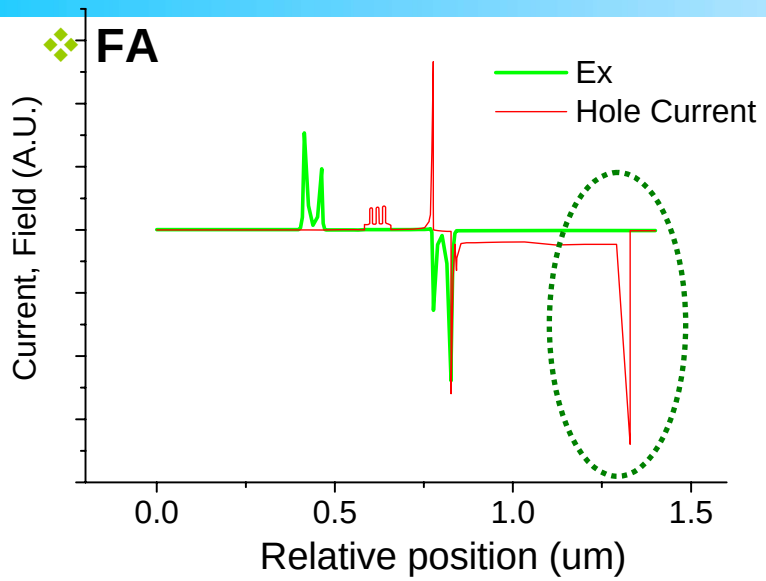
RF characteristics

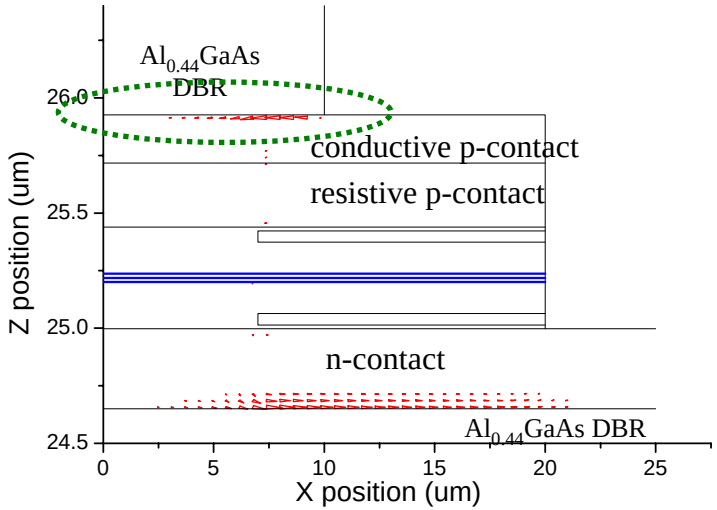


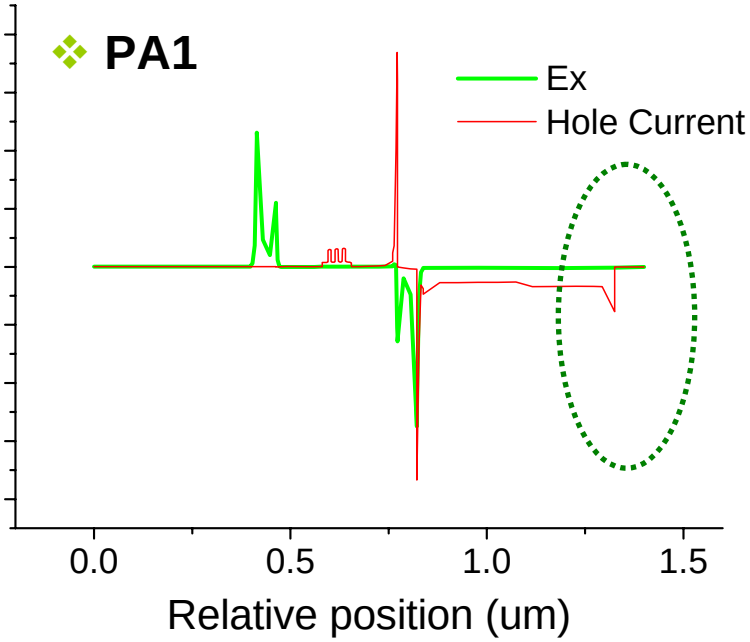
$$\varpi_R = \sqrt{\frac{v_g a}{qV_p}\eta_i (I - I_{th})}$$

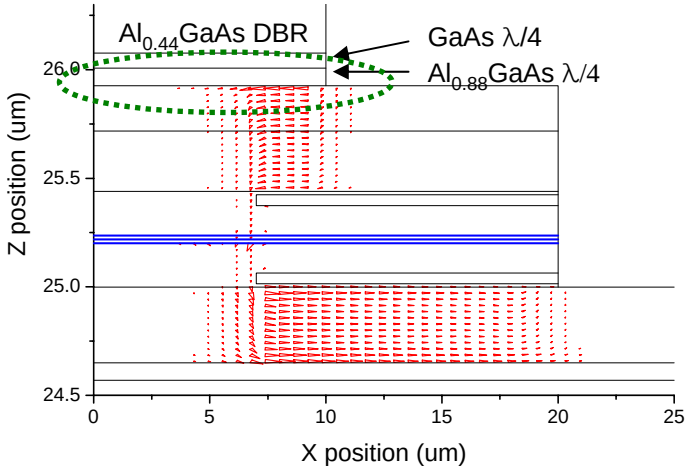
- Because of slow lateral diffusion current (unrealistic), the response of the fully-averaged (FA) case is much slower than the partially-averaged (PA) cases.

Transport effect on bandwidth









Summary

- 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.