Effects of Carrier Escape and Capture Processes on Quantum Well Solar Cells

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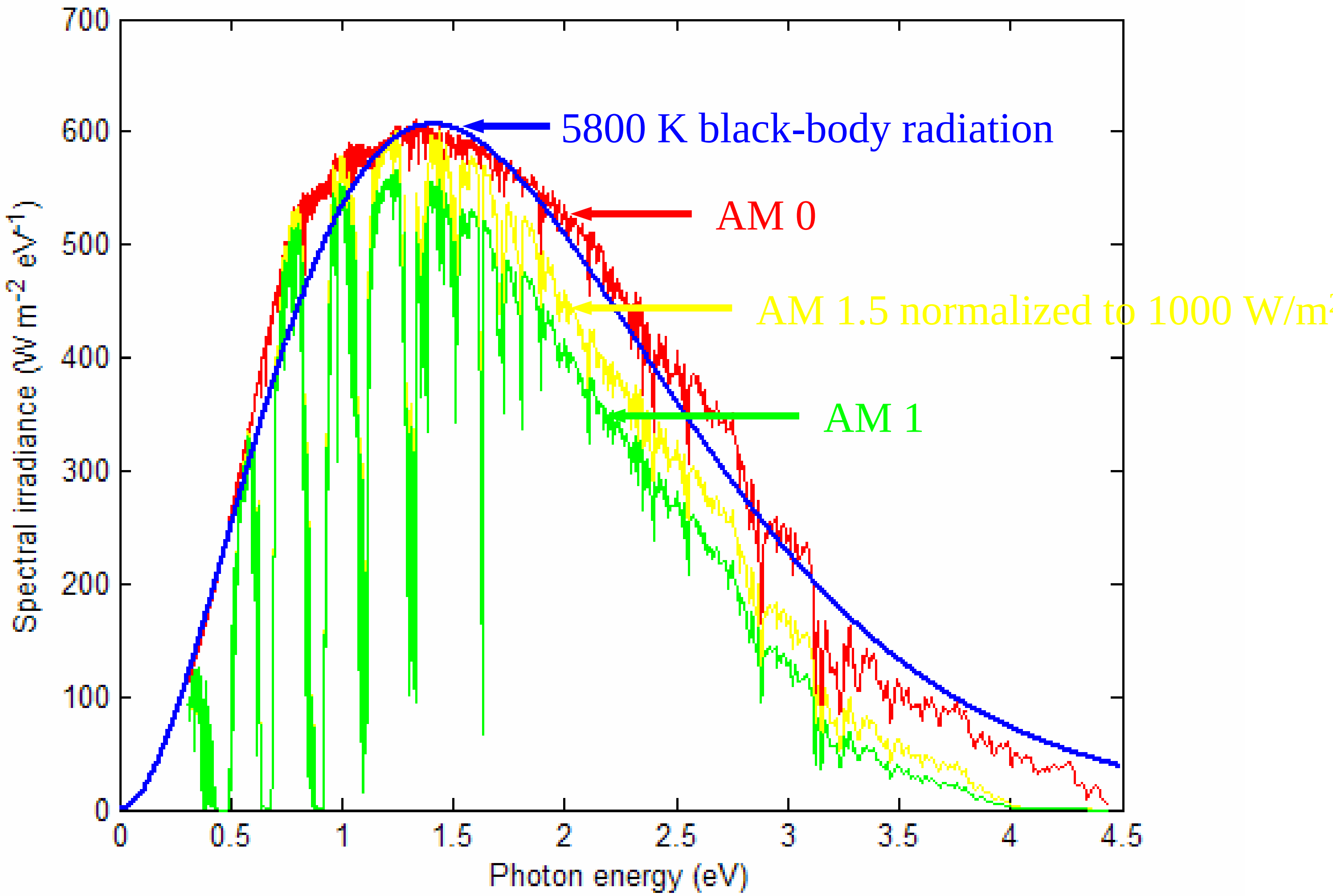
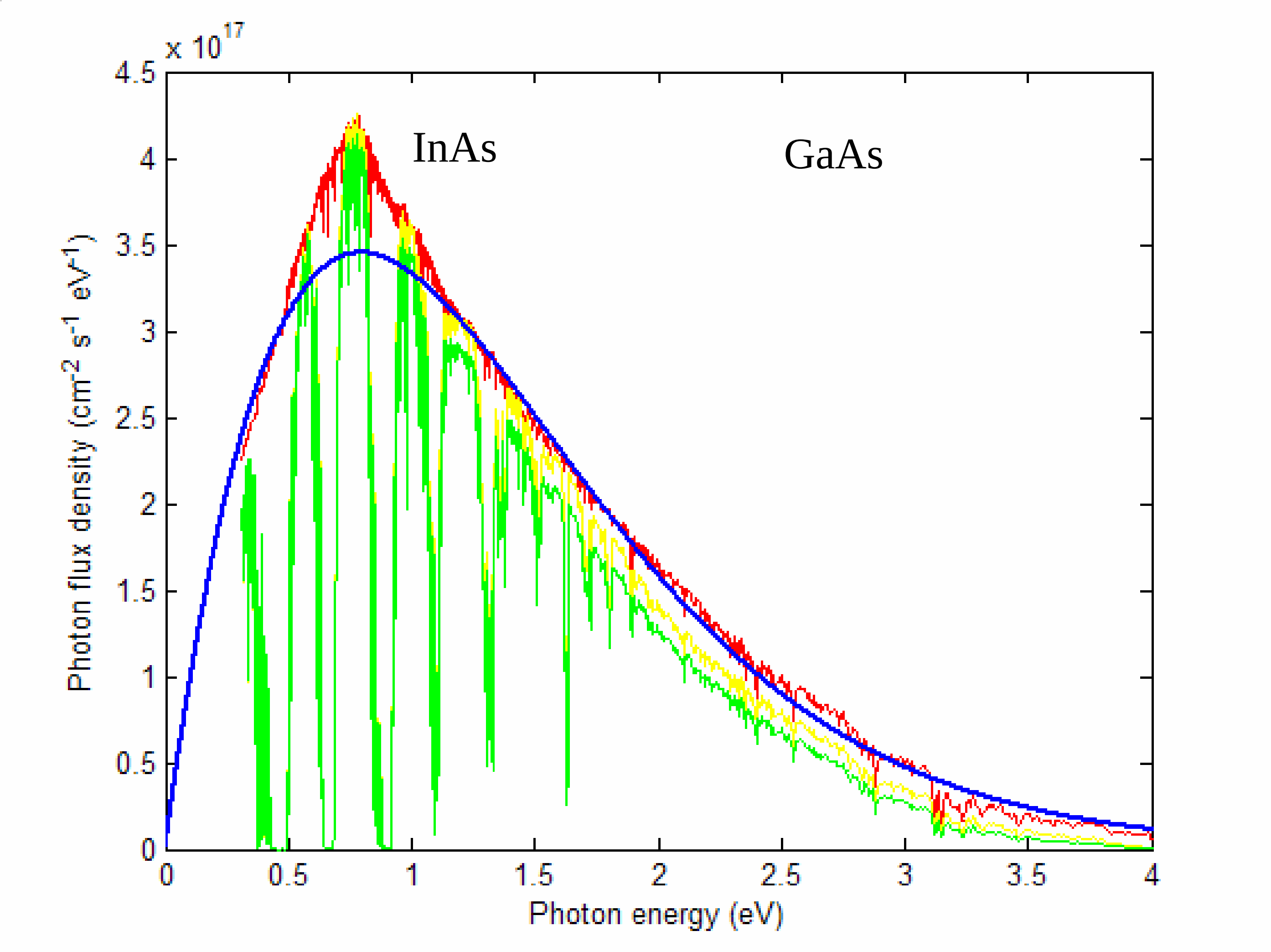
Special Thanks

Special thanks to all the members of the R&D department of the E-Ton Solar Tech. Ltd. This work is partly supported by the National Science Council of Taiwan.

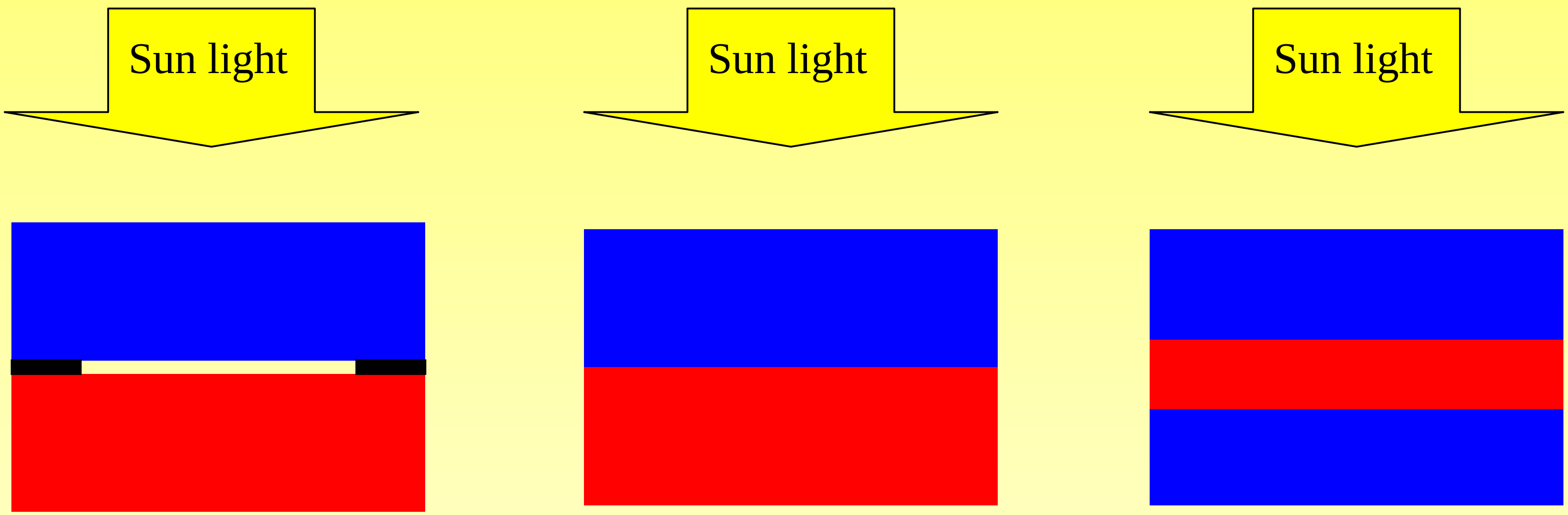
Solar Irradiance



Methods to Catch More Sun Light:
Different Materials for Different Wavelength



Methods of Integration



Mechanically stacked

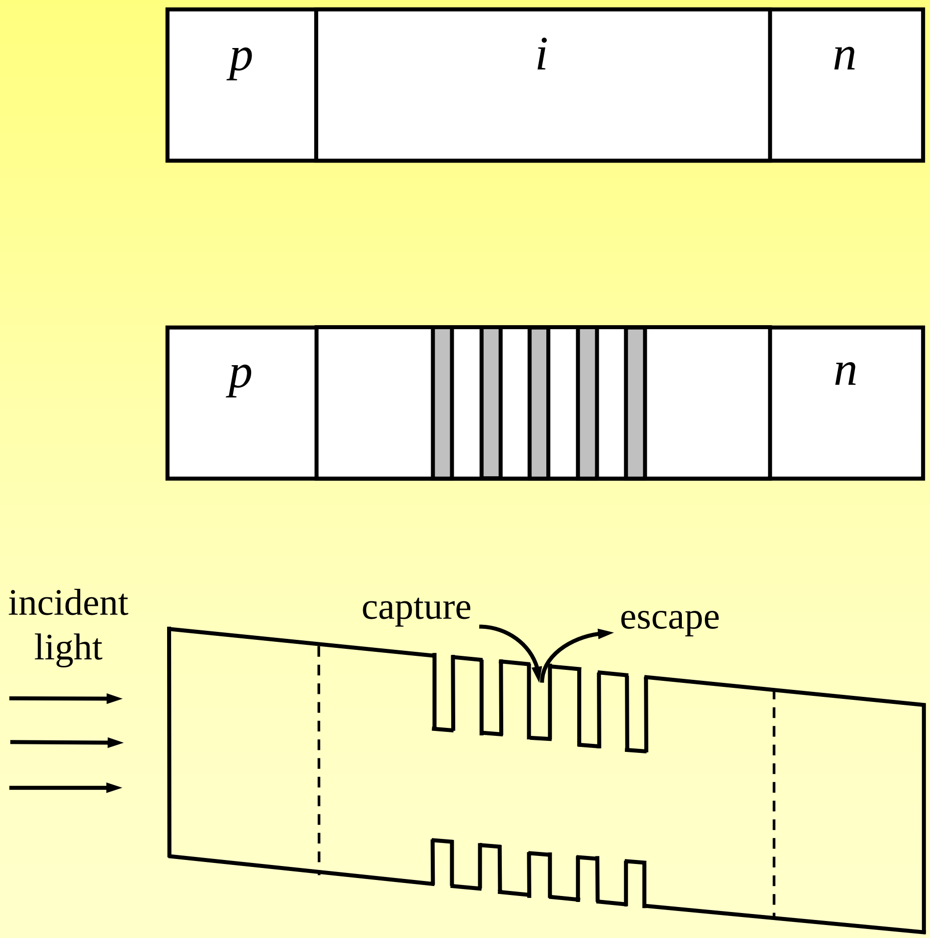
Monolithic

Tandem

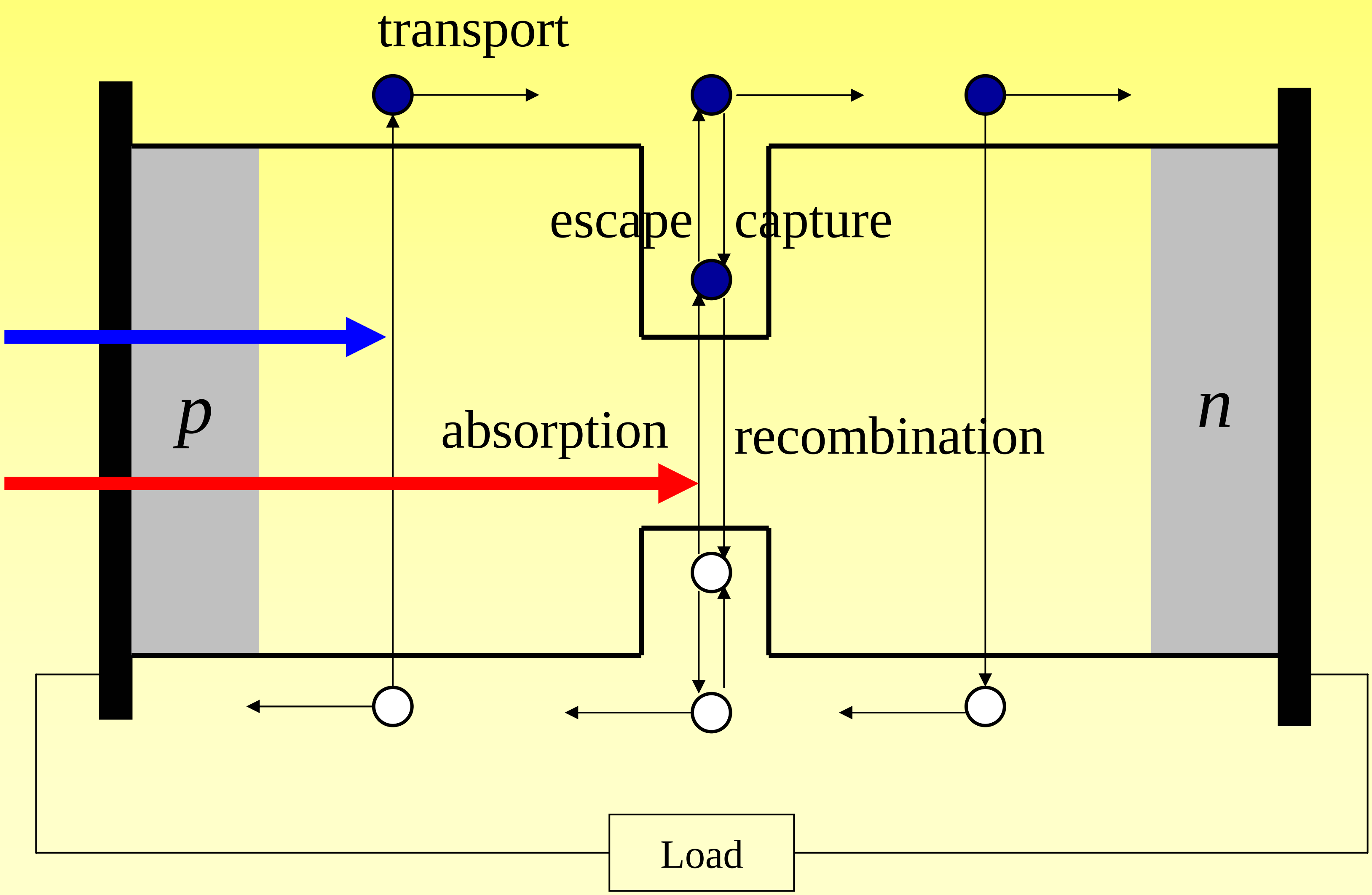
Embedded

Quantum wells, wires, dots, boxes, …,Nano-

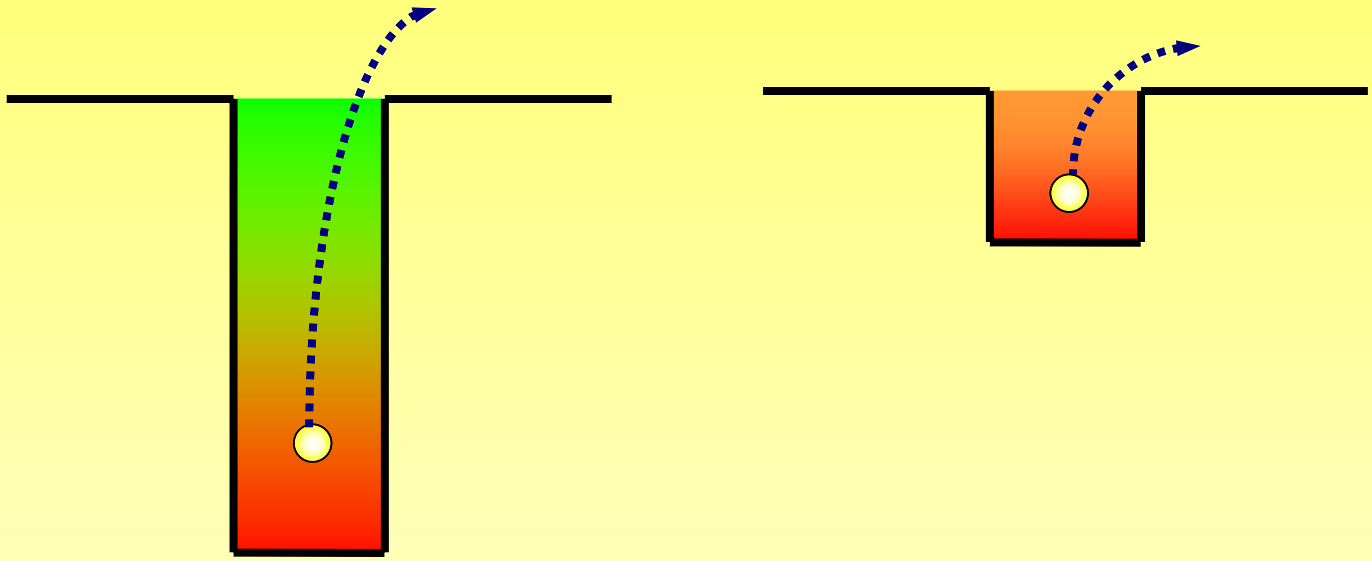
Quantum Well Solar Cells



Carrier Dynamics in QW Solar Cells



Design Issue: Potential Depth of QWs



Deep quantum well:

Large photocurrent

Slow carrier escape

Shallow quantum well:

Small photocurrent

Fast carrier escape

Theoretical Model Without Escape and Capture Processes:

The Superposition of Photocurrent and Dark Current

photocurrent → I_{light}; dark current (recombination current) → I_{dark}

$$I = I_{light} - I_{dark} = (I_{Bulk} + I_{QW}) - (I_{Rb} + I_{Rw})$$

Recombination current: $I_R = I_{SRH} + I_{rad} + I_{Auger} + I_{\text{interface}}$

Theoretical Model With Escape and Capture Processes: Rate Equations of The Charge-Control Model

escape time capture time transport time

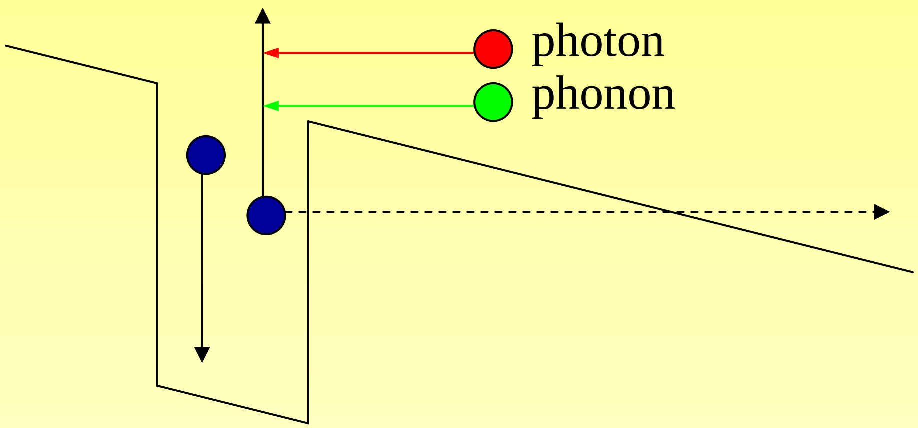
$$I_{Bulk} - I_{net} - I_{Rb} = I \qquad \frac{dN_b}{dt} = \frac{I_b}{q} + \frac{N_w}{\tau_{esc}} - \frac{N_b}{\tau_{cap}} - \frac{N_b}{\tau_b} - \frac{N_b}{\tau_d}$$

$$I_{QW} + I_{net} - I_{Rw} = 0 \qquad \frac{dN_w}{dt} = \frac{I_w}{q} - \frac{N_w}{\tau_{esc}} + \frac{N_b}{\tau_{cap}} - \frac{N_w}{\tau_w}$$

recombination time in the bulk recombination time in the QWs

Carrier Escape from a QW

- Phonon-assisted
- Photon-assisted
- Carrier-assisted
  - Intraband
  - Interband (Auger)
- Direct tunneling



Previous Work in QW Lasers

316 IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 1, NO. 2, JUNE 1995

Nonlinear Gain Coefficients in Semiconductor Quantum-Well Lasers: Effects of Carrier Diffusion, Capture, and Escape

Chin-Yi Tsai, Chin-Yao Tsai, Yu-Hwa Lo, *Senior Member, IEEE*,
Robert M. Spencer, and Lester F. Eastman, *Life Fellow, IEEE*

1088 IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 6, NO. 9, SEPTEMBER 1994

Carrier Capture and Escape in Multisubband Quantum Well Lasers

Chin-Yi Tsai, Lester F. Eastman, Yu-Hwa Lo, and Chin-Yao Tsai

Previous Work in QW Lasers

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 7, NO. 6, JUNE 1995 599

Carrier DC and AC Capture and Escape Times in Quantum-Well Lasers

Chin-Yi Tsai, Chin-Yao Tsai, Yu-Hwa Lo, *Senior Member, IEEE*, and Lester F. Eastman, *Life Fellow, IEEE*

Breakdown of thermionic emission theory for quantum wells

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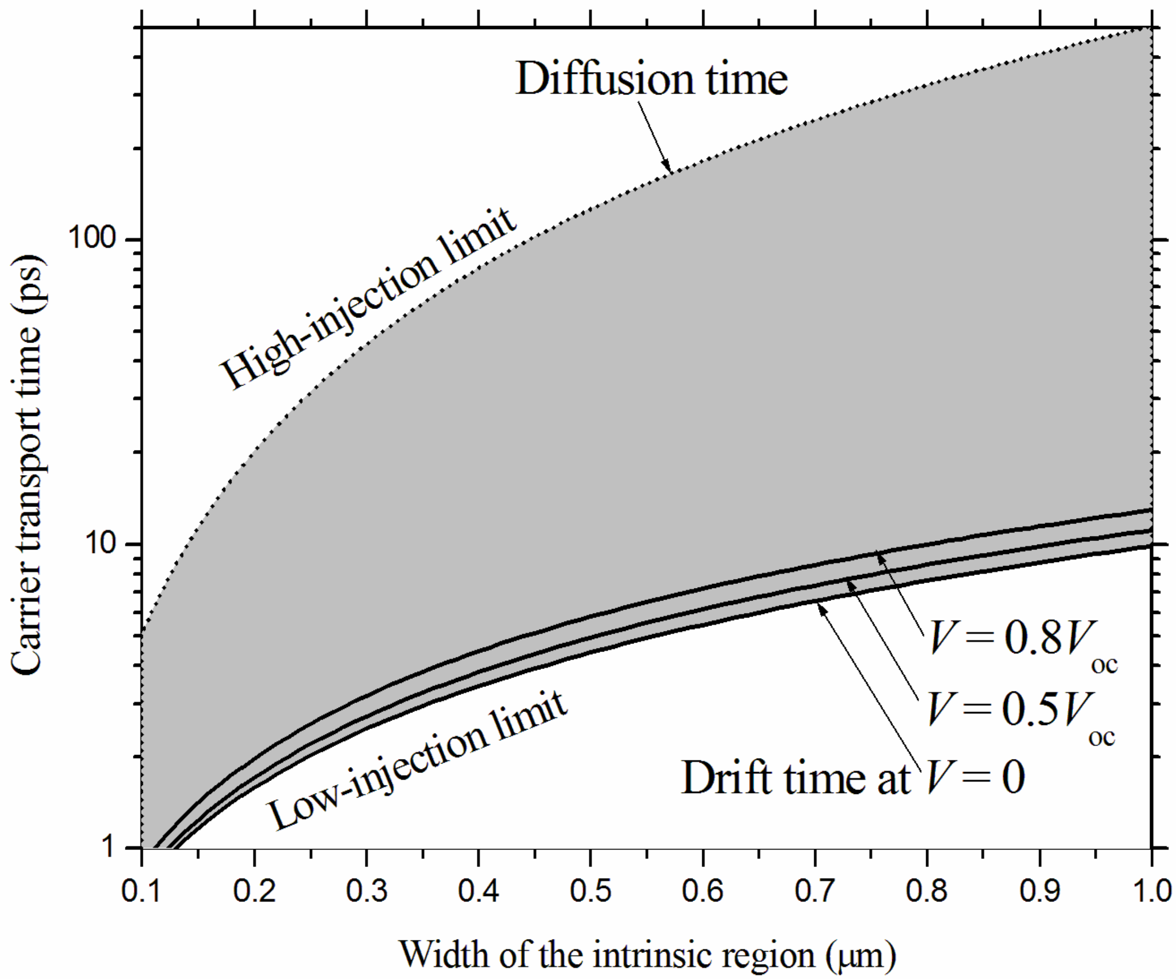
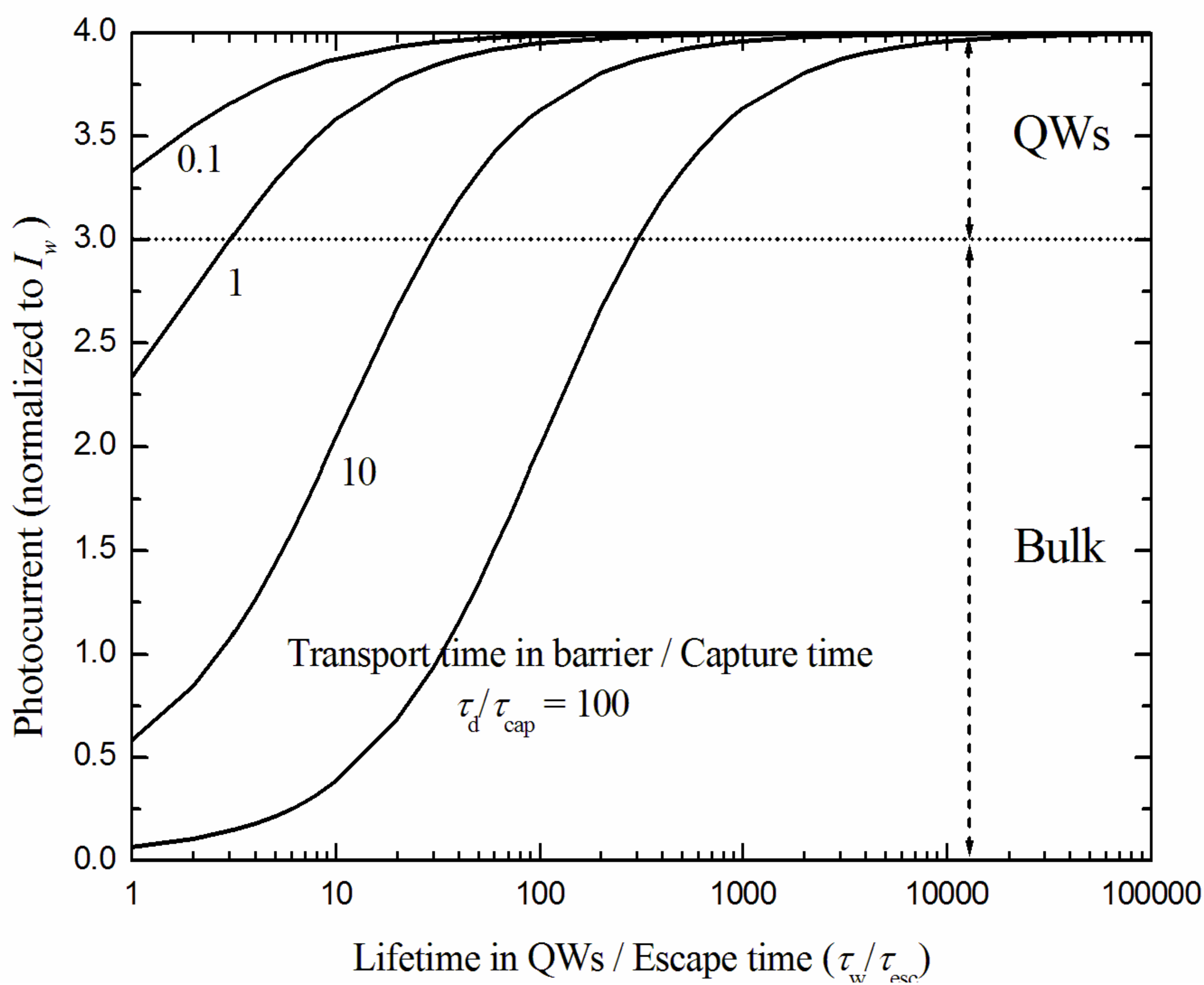
(Received 31 January 1994, accepted for publication 12 May 1994)

Carriers escape from quantum wells into barriers via carrier-polar optical phonon absorption is theoretically studied in multisubband quantum well structures. We find that carriers in each subband have their own minimum escape time when the energy difference between the band edges of the subband and the barrier matches the energy of a longitudinal optical phonon. Compared to the calculations from classical thermionic emission theory, we find that the thermionic emission theory is no longer valid when the width or the depth of quantum wells is small.

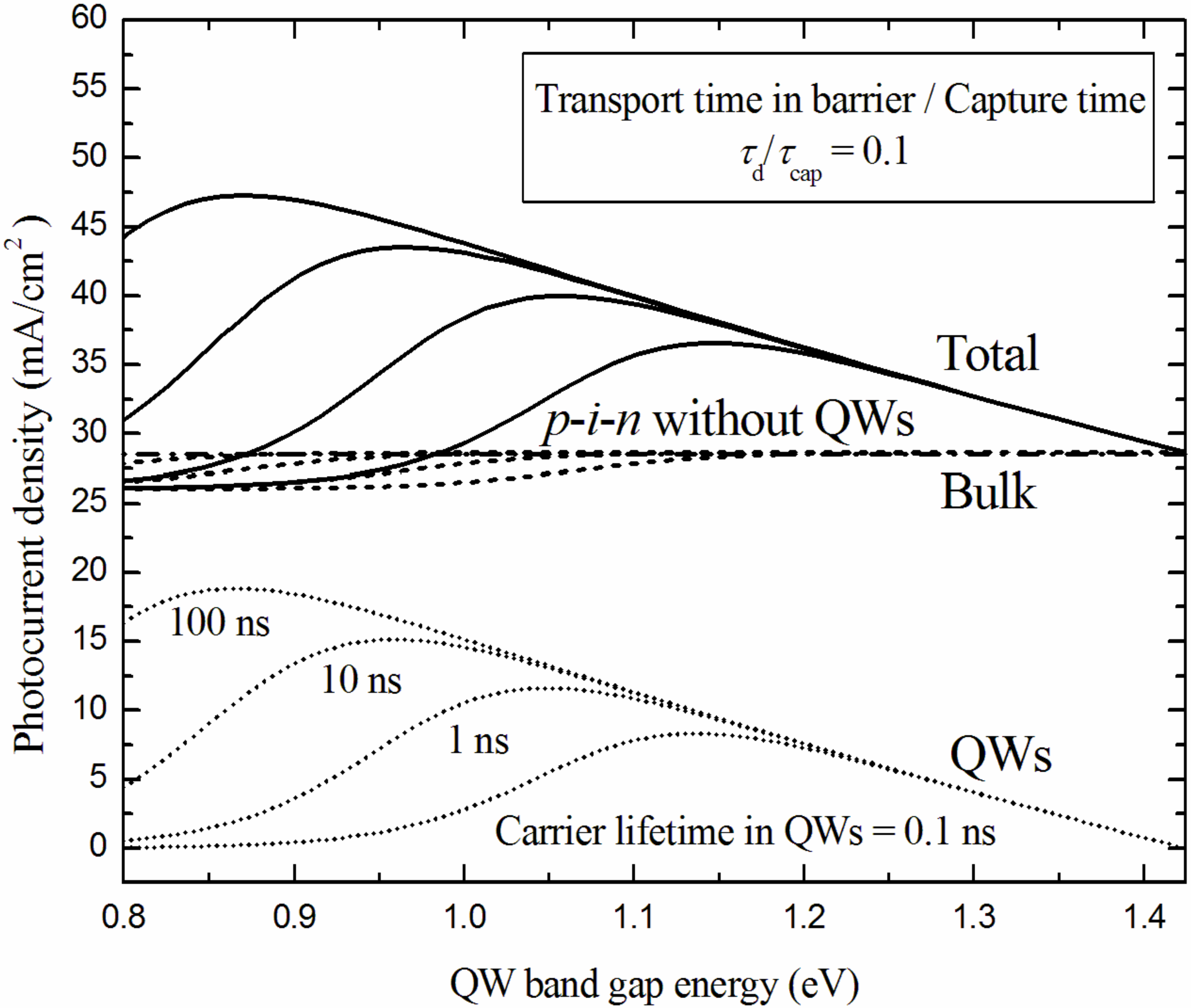
Current theoretical works in QW solar cells keep breaking down!!!

Carrier Transport: Drift and Diffusion

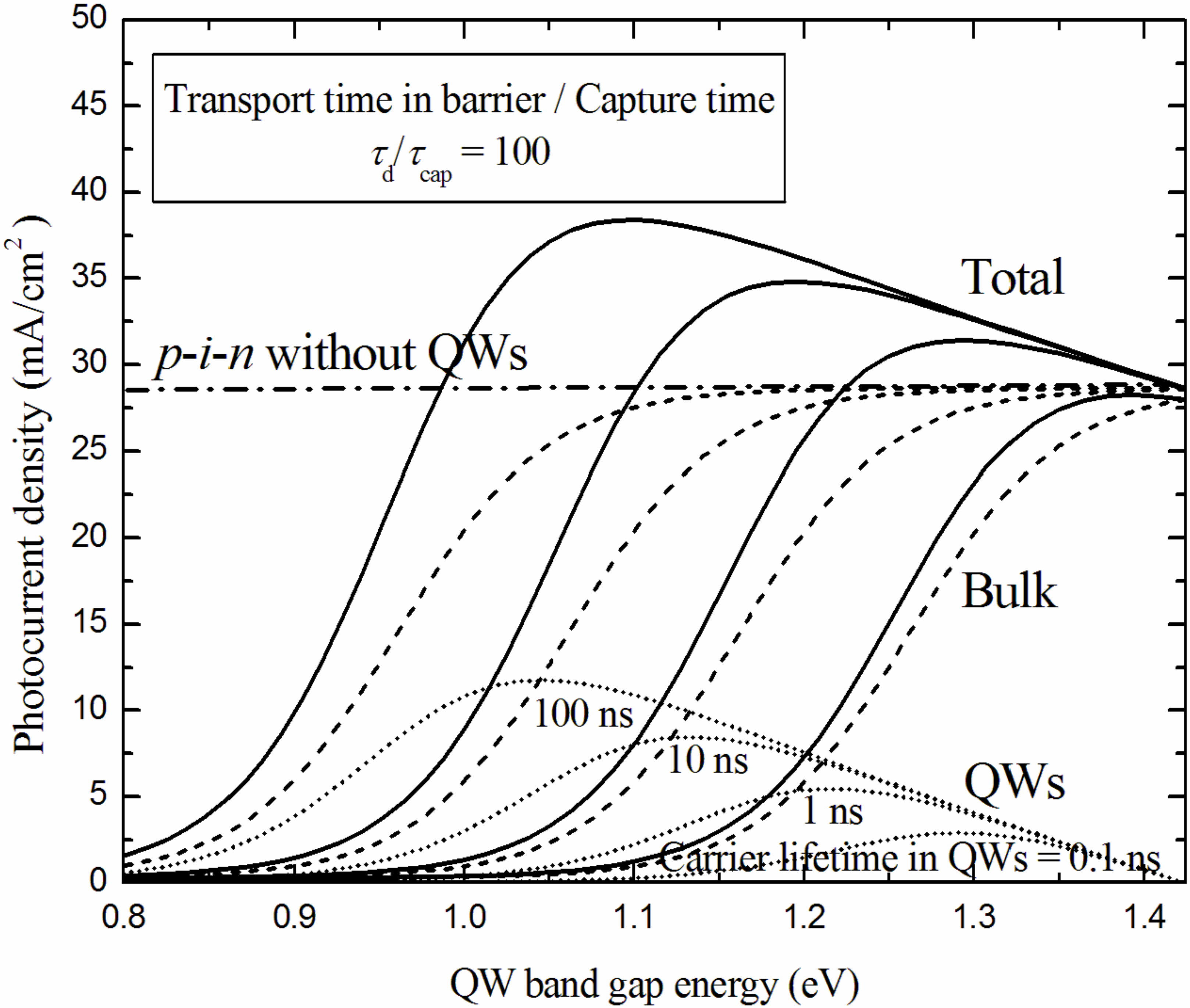




4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
10
100
1000
10000
100000
0.1
1
10
QWs
Bulk
Transport time in barrier / Capture time
$\tau_d/\tau_{cap} = 100$
Photocurrent (normalized to I_w)
Lifetime in QWs / Escape time (τ_w/τ_{esc})



Transport time in barrier / Capture time
$\tau_d/\tau_{cap} = 0.1$
Total
p-i-n without QWs
Bulk
100 ns
10 ns
1 ns
QWs
Carrier lifetime in QWs = 0.1 ns
Photocurrent density (mA/cm^2)
QW band gap energy (eV)
0
5
10
15
20
25
30
35
40
45
50
55
60
0.8
0.9
1.0
1.1
1.2
1.3
1.4



Transport time in barrier / Capture time
$\tau_d/\tau_{cap} = 100$
Total
p-*i*-*n* without QWs
Bulk
100 ns
10 ns
QWs
1 ns
Carrier lifetime in QWs = 0.1 ns
Photocurrent density (mA/cm^2)
QW band gap energy (eV)
0
5
10
15
20
25
30
35
40
45
50
0.8
0.9
1.0
1.1
1.2
1.3
1.4

Conclusion

- Solar cells with very deep QWs will suffer from extremely slow escape processes and their photocurrent can even be inferior to their bulk counterparts.
- There exists an optimal band gap energy of a QW material for achieving maximum photocurrent.
- Only if the escape time is at least two-order of magnitude larger than the carrier lifetime in QWs, then solar cells have the benefits from QW structures.
- Similar models can be applied to other problems, such as quantum dot, intermediate bands, or nano-materials.