Semiconductor Devices - 2014

Lecture Course
Part of
SS Module PY4P03

Dr. P. Stamenov

School of Physics and CRANN, Trinity College,
Dublin 2, Ireland

Hilary Term, TCD
21th of February '14

MAGNETISM & SPINTRONICS
Trinity College Dublin

CRANN

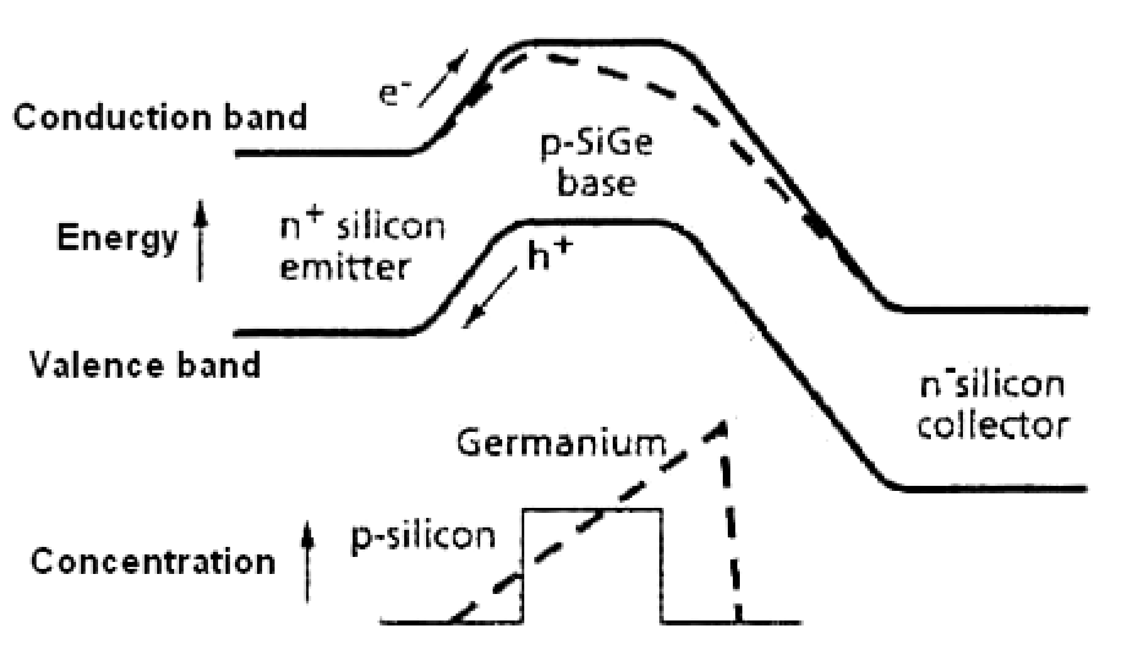
Notes on Bipolar Transistors

- The emitter efficiency for minority electron injection into the base is almost ideal (negligible hole current).
- The emitter can be *lightly* doped (reduces base-emitter capacitance) and the base *heavily* doped (reduces base resistance). This is the reverse of the doping requirements in a homojunction BPT.
- The heavily doped base can be very thin, as the Early effect can now be neglected – i.e. the base-collector depletion layer extends into just the collector, so punch-through in the base cannot occur.
- The common emitter current gain is very high, $>> 10^3$, as is the frequency response, even though carrier lifetimes in GaAs are short (direct gap semiconductor) – the electrons are simply substantially faster.
- Having another handle on band gap and band alignment can only be a positive advantage...

...Continued

- In a Si 'homojunction' BPT, with emitter doping above 10^{23} m^{-3} the band gap shrinks by ~ 2 or 3 x kT/e.
- This significantly reduces the emitter efficiency, and is a fundamental limitation in Si BPTs.
- This leaves an emitter-base *heterojunction* as a viable alternative, but this time with an *increased* barrier to minority carrier injection into the base from the emitter.
- HBTs (with *increased* injection into the base, as desired) can also be made using a Si emitter and collector, and a strained SiGe narrow bandgap base.
- Note that, electron mobilities are lower than in GaAs and InP, so Si / SiGe BPTs are not as fast as GaAs and InP BPTs.
- However, most of the bulk mobility advantage of GaAs and InP is 'eaten away' by the well-developed strain control in SiGe!

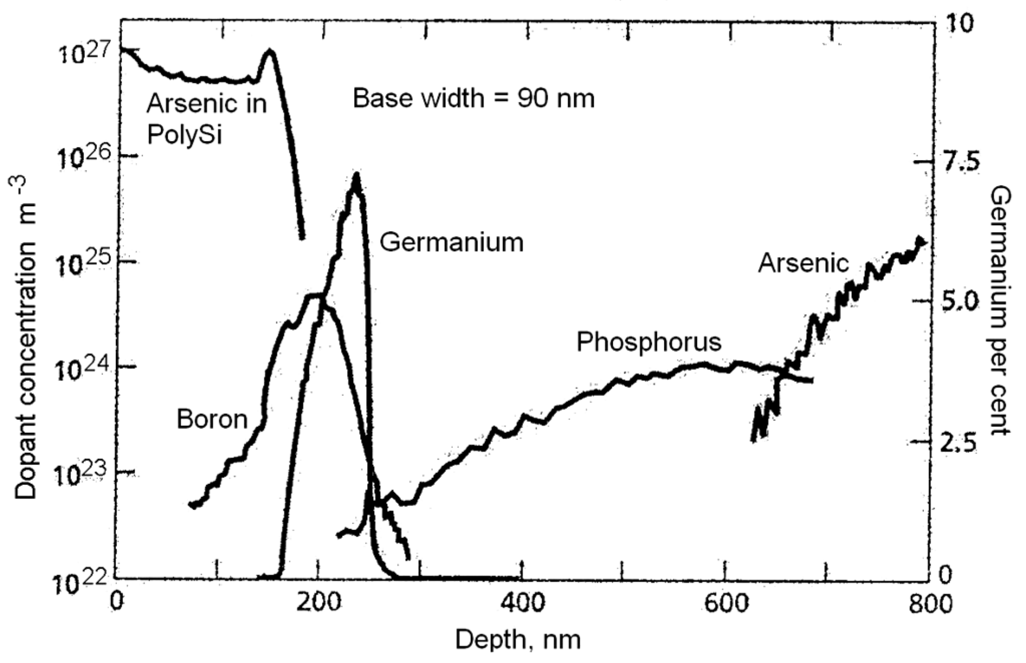
Graded Doping



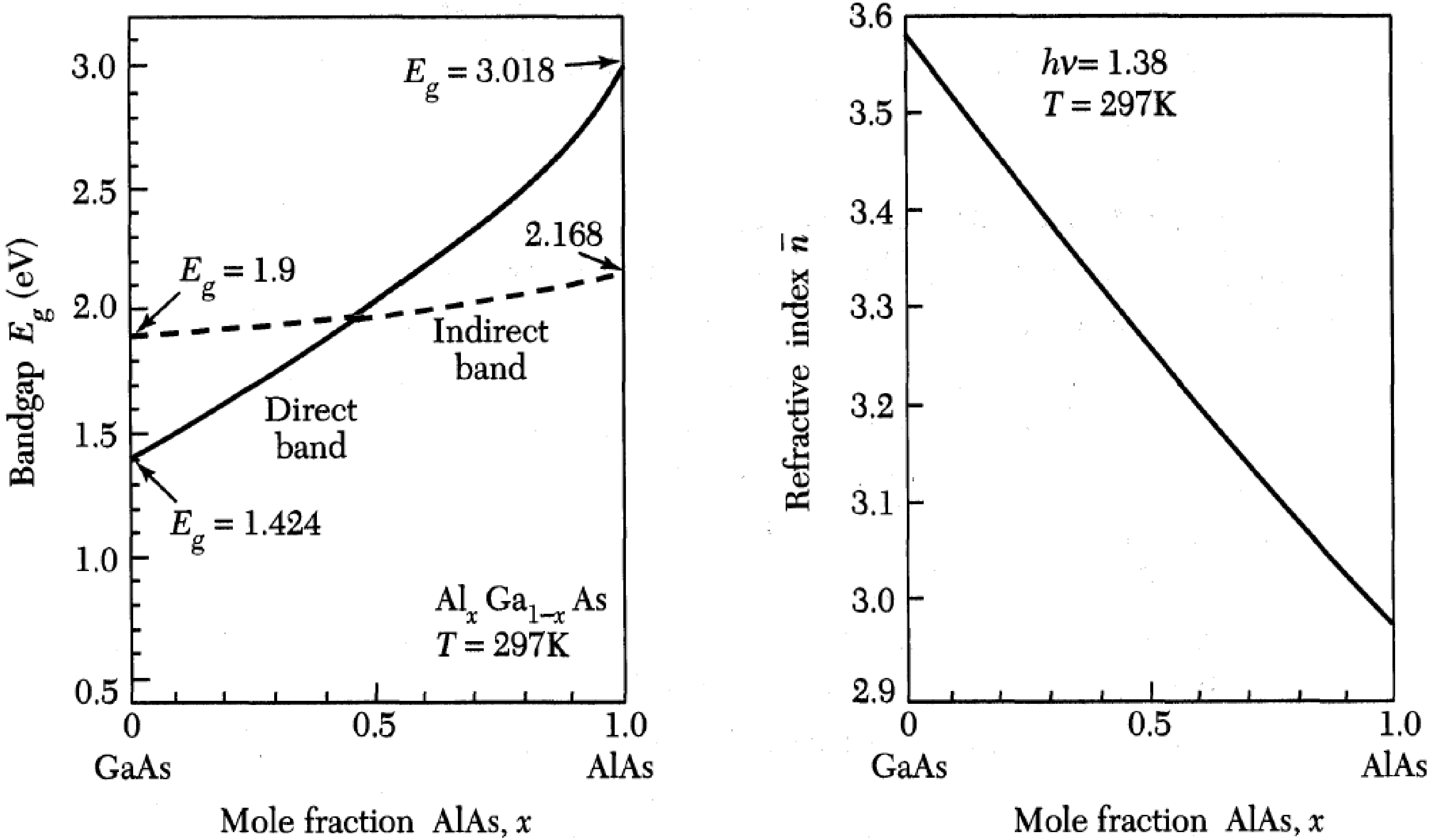
- The band gap in the base can be graded by increasing the Ge proportion in the SiGe base going from emitter to collector. (Sloping band means also a build-in effective electric field!)
- This makes the base conduction band edge slope down while keeping the base valence band approximately level (with its high number of majority holes – level pinning at the acceptor energy level).
- This gives an electron energy gradient and an electron quasi-electric field up to 5 times larger than the base field produced by the dopant concentration gradient in a planar homojunction BPT. (Think about alloying vs. diffusion doping...)

From Homojunction to Heterojunction

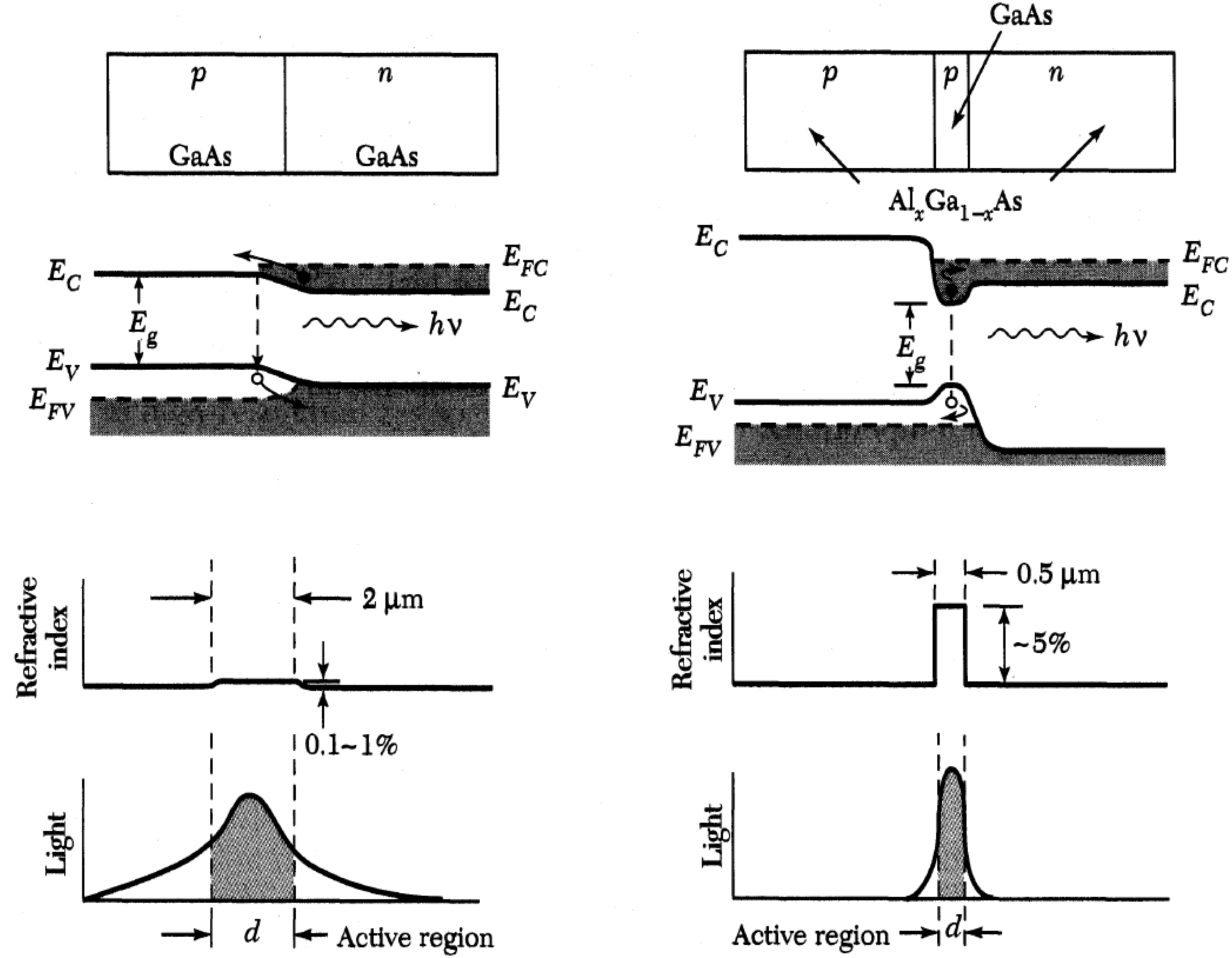
- This decreases the base transit time and increases the current gain and frequency response.
- A similar principle can be applied to a GaAs HBT by using an AlGaAs base and grading the Al fraction (optoelectronic materials!).
- J.D. Cressler reports a SiGe HBT frequency response of 510 GHz (at 4.5 K! – 352 GHz at 300 K) - R. Krithivasan, Yuan Lu, J. D. Cressler *et al*, IEEE Electron Devices Letters 27 (2006) 567 – 569.
- The picture shows the impurity profile, as obtained from secondary ion mass spectroscopy, of an early (~1990) SiGe HBT from IBM.
- J. D. Cressler, IEEE Spectrum 32 No 3 (1995) 49 - 55.



GaAs-AlAs Gap and Refractive Index



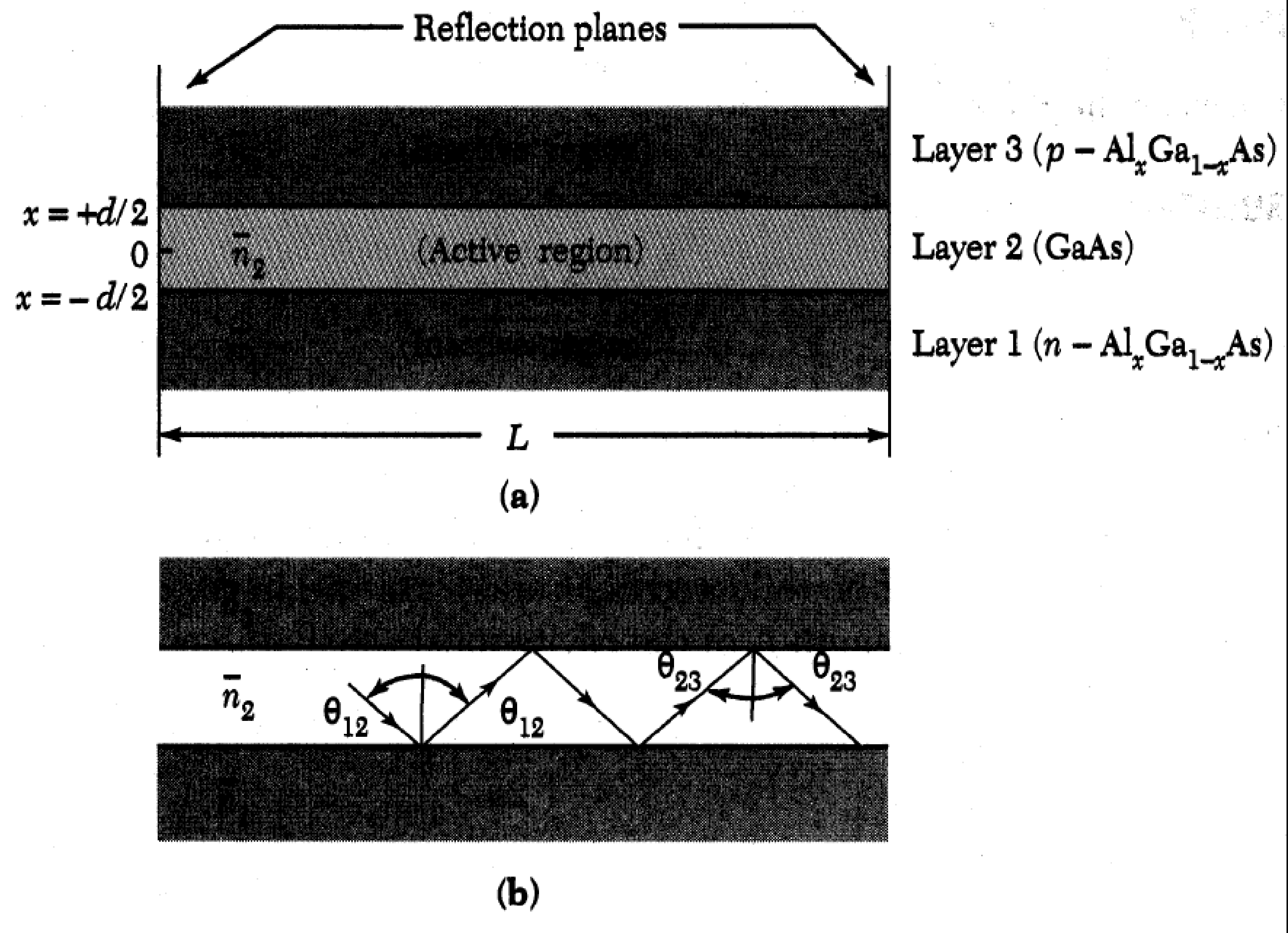
Homojunction vs. Heterojunction LEDs

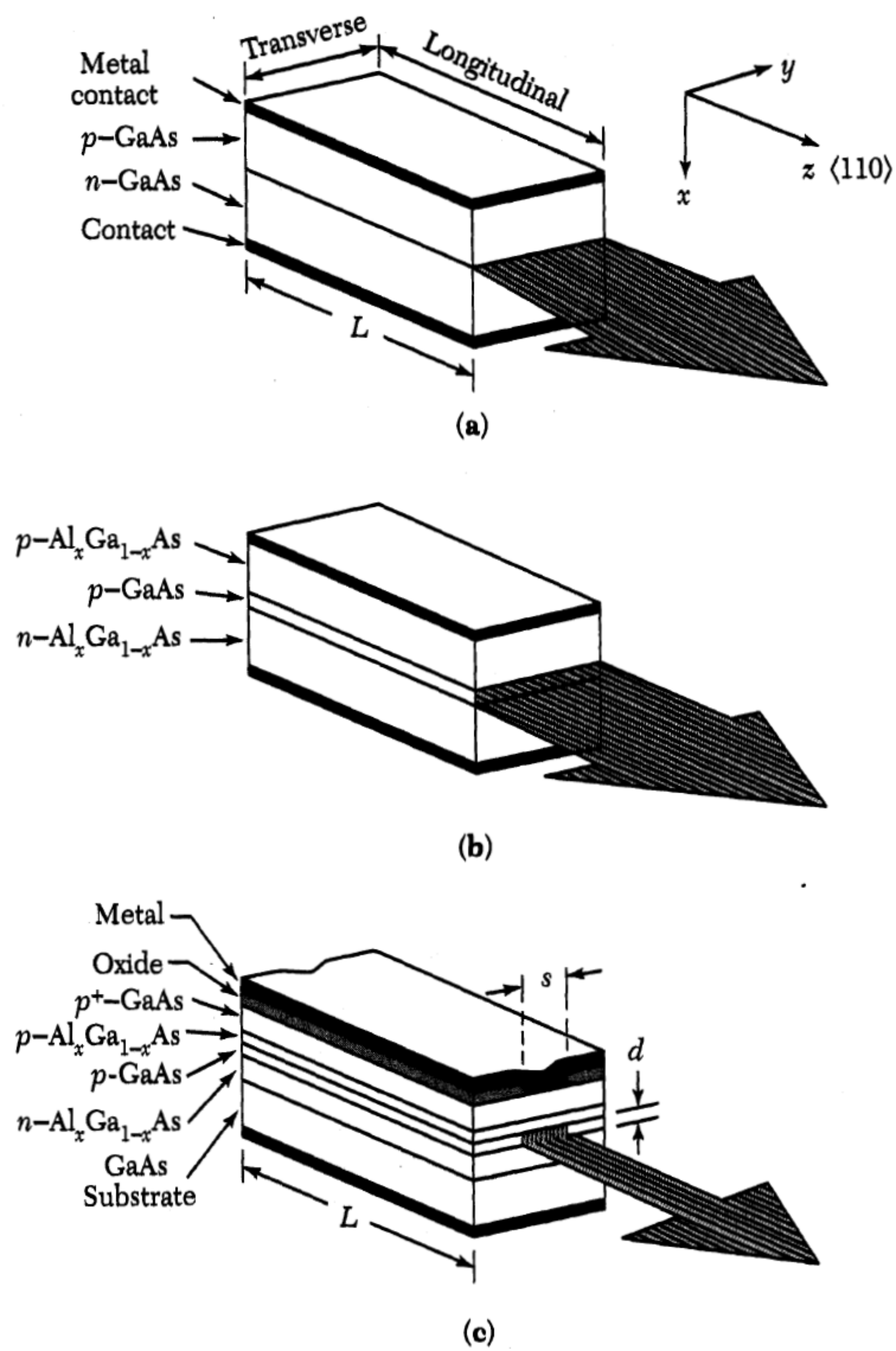


(a)

(b)

GaAs-AlGaAs – Light Waveguides

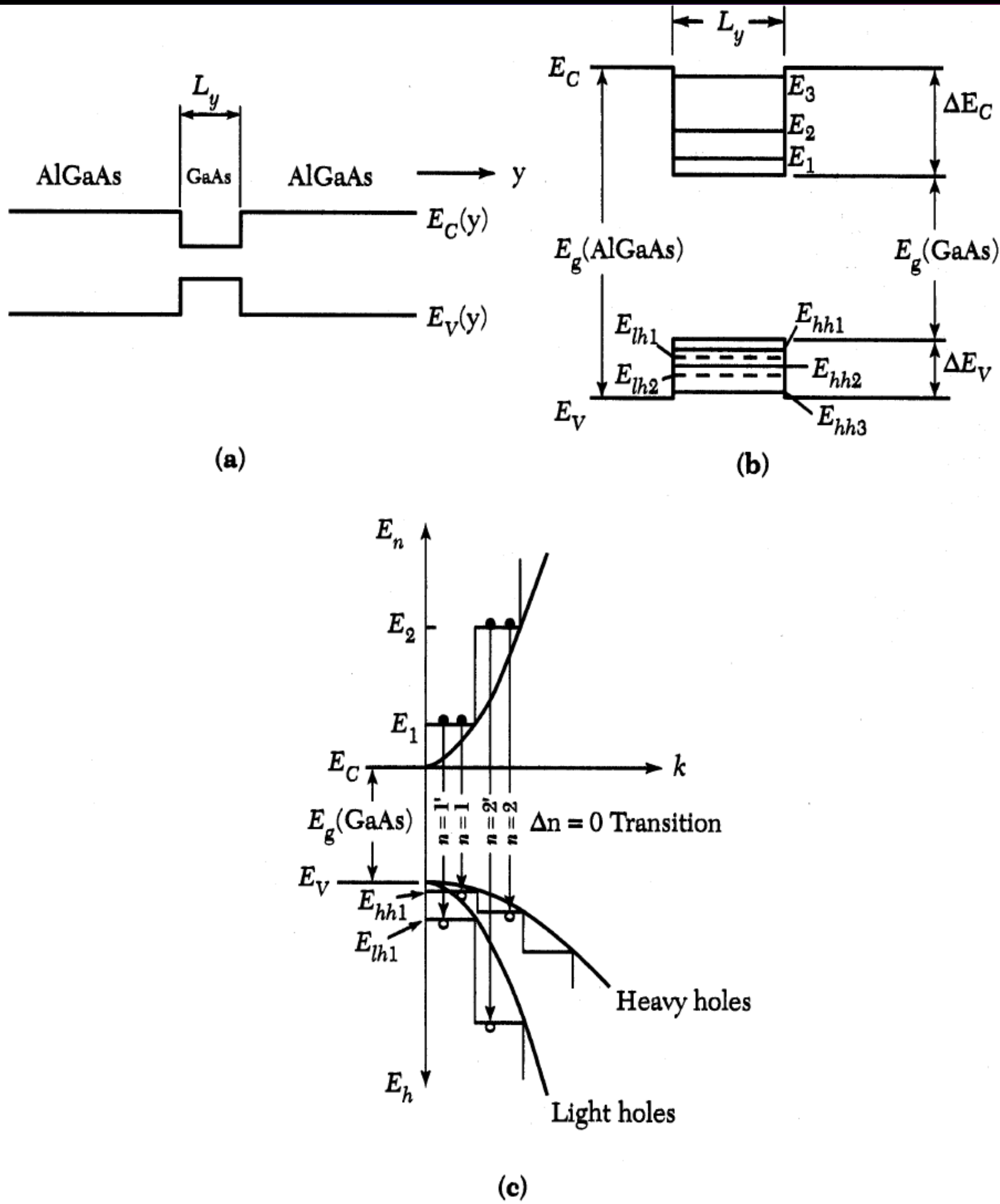




Solid State Lasers

- Convenient mirror formation via cleaving and often metallisation.
- Heterojunction-based LASERS offer higher flux.
- Additional mode selection is performed by the Fabry-Perot resonator.
- Other possibilities for achieving mode selection.
- Laterally confined beams
- Threshold current density and Joule dissipation problems
- Quality of the emitted spectrum and frequency response.

Quantum Well Basics



- Formation of quantum wells in the GaAs-AlGaAs system.
- Close to descrete micro-bands – QW states.
- Radiative vs Non-radiative Transitions.
- Manufacturing of Quantum Well structures.
- Applications in emission and sensing
- Flexibility of the design parameters and performance characteristics.

Quantum Wells and Deep IR Emission

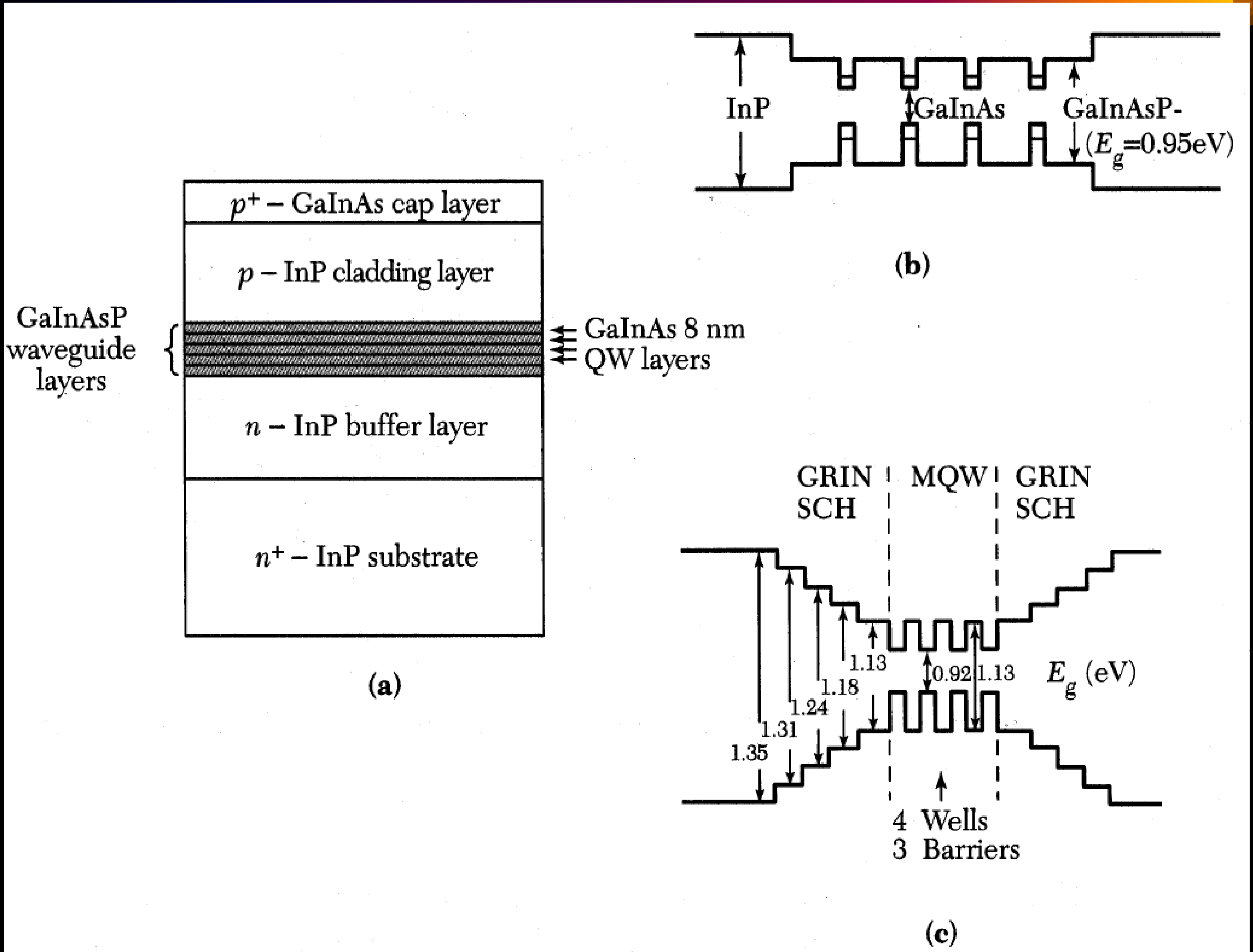
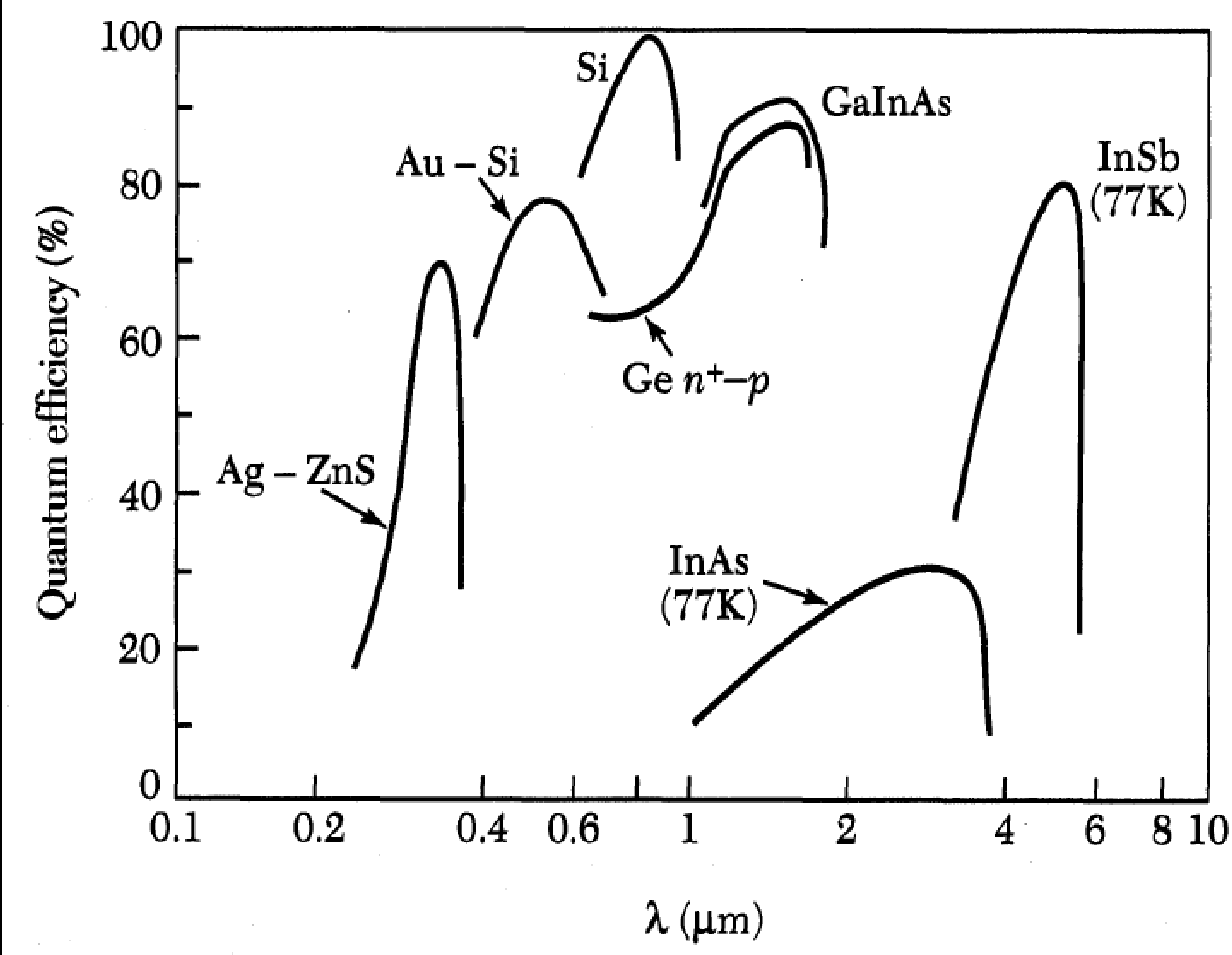
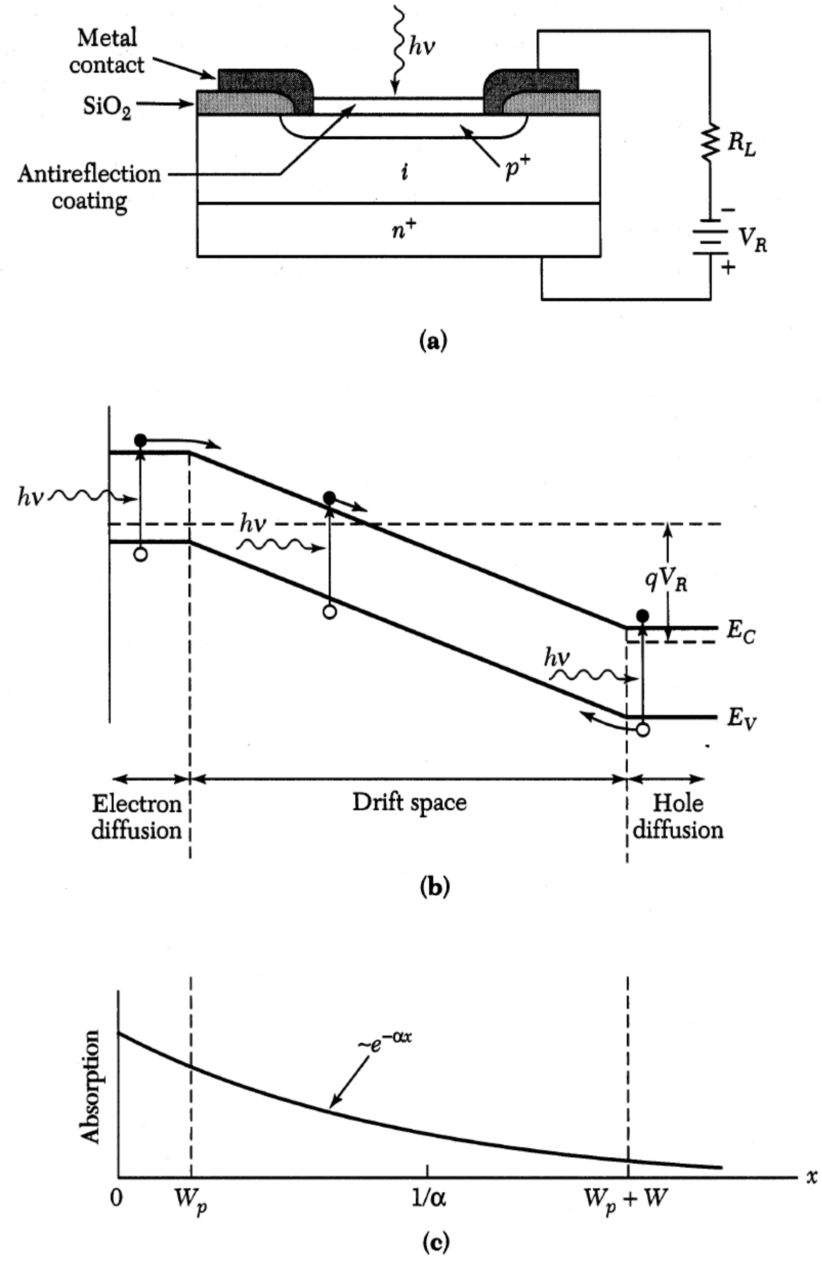
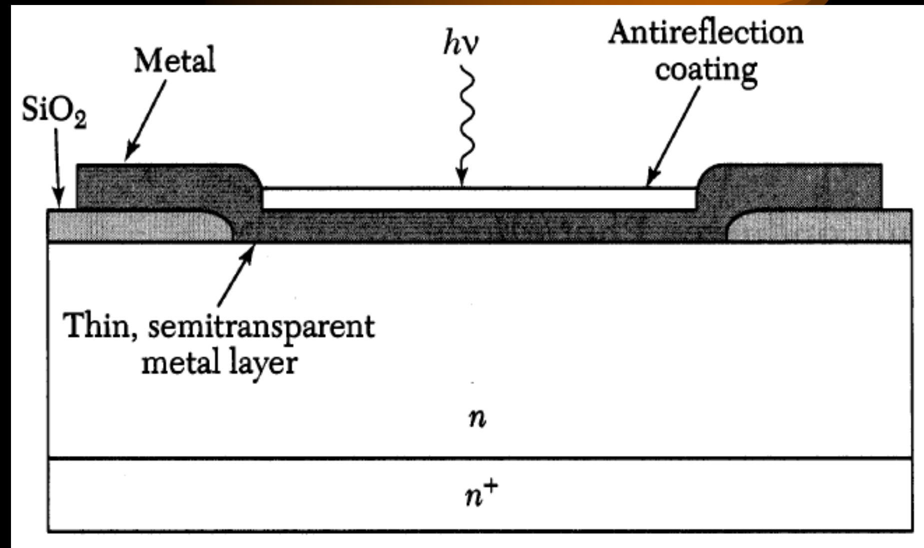


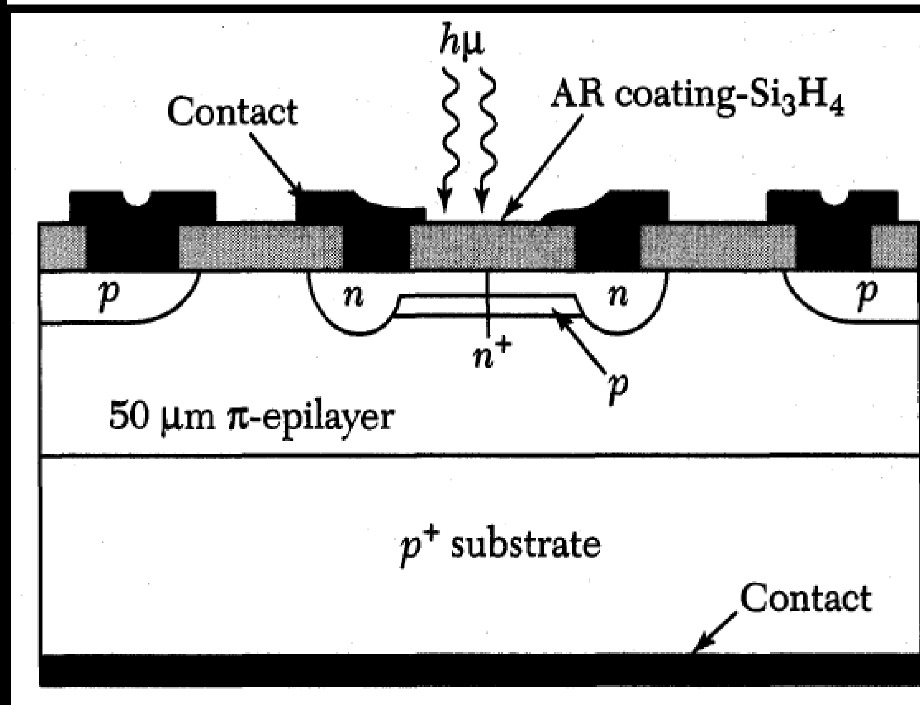
Photo-diodes as Detectors



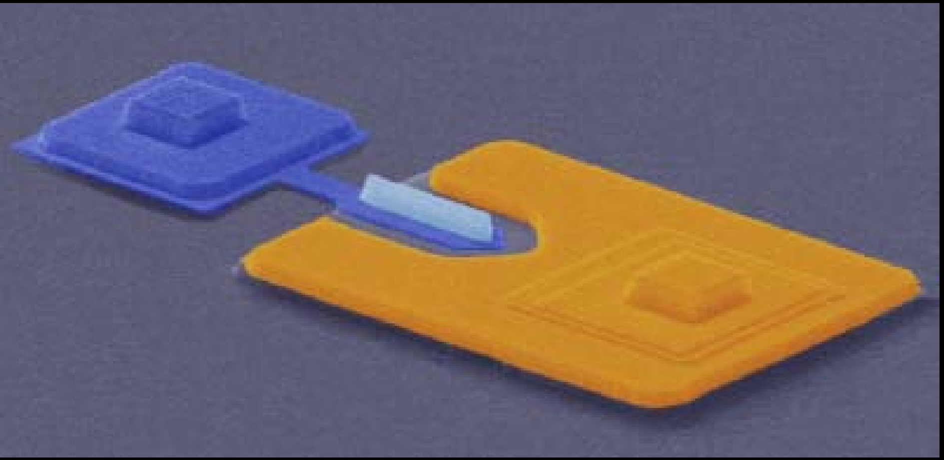
Various Photodiode Structures



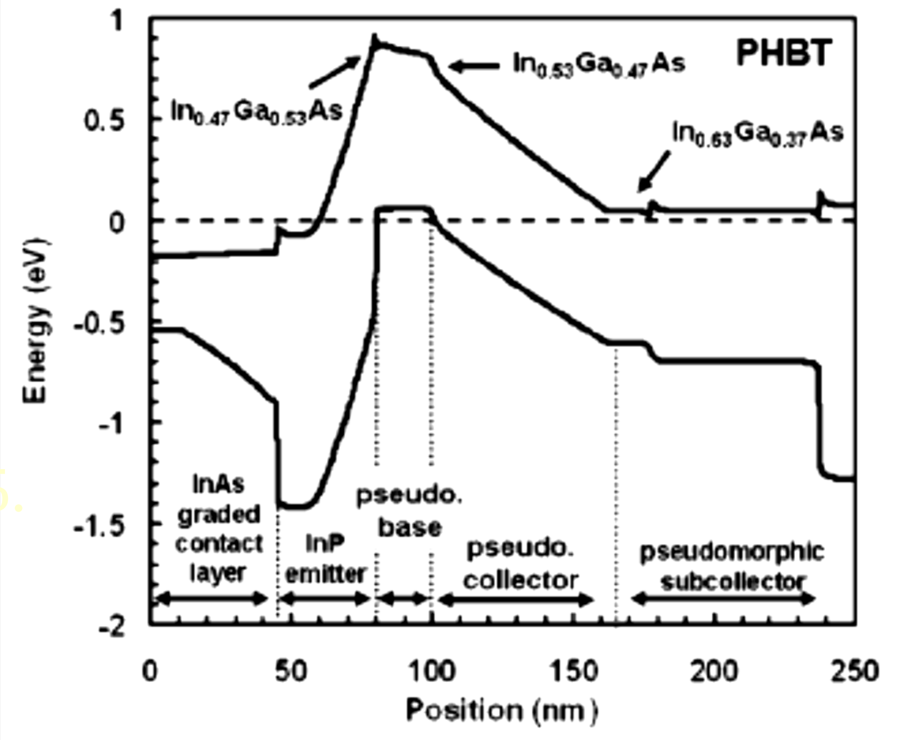




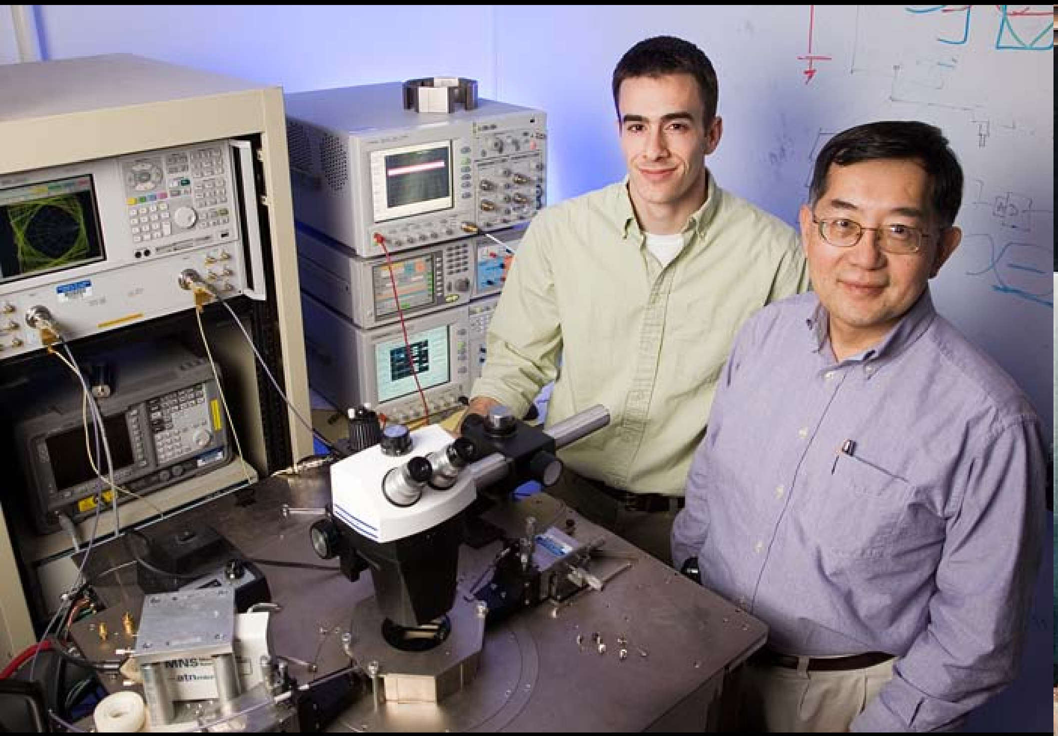
The Fastest Transistor?



- The fastest transistor is possibly a pseudomorphic graded base (and graded collector) InP/InGaAs HBT, with a frequency response of 845 GHz at –55°C (Snodgrass, Hafez, Harff and Feng, 2006).
- An HBT, showing terminals for the base (dark blue, 12.5 nm wide), emitter (light blue, 0.32 μm x 4 μm) and collector (yellow, 55 nm).
- The picture on the right shows the energy band diagram of a similar device the same group made in 2005.
- 845 GHz already corresponds to a wavelength of only 355 μm!



The First and the Latest (Fastest)...



- Feng (right) and Snodgrass (left) with their record-breaking bipolar transistor – Illinois, like Bardeen.
- Bardeen, Shockley *et al* should have been pleased that the fastest transistors are (probably) BPTs ...
- Bardeen, Brattain and Shockley with their transistor in Bell Labs – presumably, Illinois.

What Next? Beyond Electronics?

- Electronics (~100 GHz – C, ~500 GHz – Si, ~850 GHz – InGaAs)
  - Well developed for a very large number of applications
  - To reach fundamental limits in speed, density and dissipation
- Optoelectronics (~10 GHz - InGaAs)
  - Well developed for communications
  - Manipulation is difficult and often energy consuming
- Spin electronics (~1 GHz - CoFeB)
  - Well developed for sensing and storage applications
  - Manipulation is difficult but possible with lower dissipation
- Multiferroics, Nanomechanics, etc. (~1 GHz – BFO, ~100 MHz -SiN)
  - Still in their infancy
  - Some of them may produce viable options for interfacing, sensing and storage applications

Thanks and Acknowledgements

Thank You Very Much for Your Attention!