6.772 - Compound Semiconductor and Heterostructure Devices

Lecture 23 - **Detectors II; Modulators** - Outline

- **Photocapacitors**
  - CCDs

- **Photodetectors with gain**
  - Avalanche photodiodes
  - Pin-diodes with TIA
  - Photoconductors
    - Conventional PCs
    - Quantum intersubband photo-detectors (QWIPs, QDIPs)

- **Optical to electrical energy conversion**
  - General issues in photovoltaic diode design
  - Multi-junction solar cells
  - Thermo-photovoltaic cells

- **Modulators**
  - Moving to Lecture 24
    - Waveguide structure based modulators
    - Coupler-based; Mach-Zehnder based
    - Multiple Quantum Well based modulators
      - (surface-normal; waveguide geometry)
    - Silicon based modulators
Semiconductor Photodetectors - **photodiodes, photoconductors, and photocapacitors**

**Photodiode:** \( I(t) = a \times L(t) \)

**Photoconductor:** \( G(t) = a \times L(t) \)

**Photocapacitor:** \( Q(T) = a \times \int_T^T L(t) dt \)
What if we don't have an n-region adjacent to a MOS capacitor?

The **two-terminal** n-MOS capacitor

Right: Basic device

For $v_{GB} \leq V_T$ nothing is different, but when $v_{GB} > V_T$, where do the electrons for the inversion layer come from?

They diffuse to the edge of the depletion region from the bulk. This is like reverse bias diode saturation current and it takes a long time to build up the inversion layer charge.
The MOS light detector -

What if we shine light on our biased MOS capacitor?

$v_{GB} > V_T$

Electrons optically generated in and near the depletion region will be populate the inversion layer. The number collected in a frame time (clock period) is proportional to the light intensity.
Two adjacent MOS capacitors:

\[ V_{G2S} > V_{G1S} > V_T \]

The charge can be passed back and forth between them.
Charge-coupled devices, CCDs

An array of closely spaced 2-terminal MOS capacitors can be used to (1) capture an image, and (2) shift the pixel intensity data out in a serial bit stream.
Charge-coupled devices; CCD imagers

\[ \phi_1 > \phi_3 > \phi_1 > V_T \]

\[ \phi_2 > \phi_1 > \phi_2 > V_T \]

\[ \phi_3 > \phi_2 > \phi_1 > V_T \]
CCD read-out circuitry -

The charge is shifted along and read serially using a reverse biased diode and MOS source followers.

Lifted from a Kodak website:

Fonstad/Palacios, 5/5/09
Semiconductor Photodetectors - photodiodes, photoconductors, and photocapacitors

Photodiode: \( I(t) = a \times L(t) \)

Photoconductor: \( G(t) = a \times L(t) \)

Photocapacitor: \( Q(T) = a \times \int^T L(t) \, dt \)
**Photoconductivity and photoconductors:**

When we shine light on a semiconductor that generated hole-electron pairs we change the conductivity of that material, and this change can be used to sense the presence of light.

Consider steady-state light resulting in:

\[ g_L = G \quad \Rightarrow \quad n' = p' = G \tau_{\text{min}} \]

This in turn changes the conductivity:

\[ \sigma = q \left[ \mu_e (n_o + n') + \mu_h (p_o + n') \right] \]
\[ = \sigma_o + qn'(\mu_e + \mu_h) \]
\[ = \sigma_o + \sigma' \]

And if the sample had contacts on either end, and a voltage applied to it, the current through the leads would change in response to the light. This is photoconductivity:

\[ i_D = \sigma \frac{w \cdot t}{l} v_{AB} = \left( \sigma_o + \sigma' \right) \frac{w \cdot t}{l} v_{AB} \]
\[ = I_D + i_d \quad \text{with} \quad i_d = \sigma' \frac{w \cdot t}{l} v_{AB} = qG\tau_{\text{min}} (\mu_e + \mu_h) \frac{w \cdot t}{l} v_{AB} \]
**Photoconductive Gain:**

Photoconductors have gain, i.e. a little light can result in a large current. To see how this comes about, we begin by defining the gain as the current, $i_d$, divided by $q$ times the absorbed photon flux.

The absorbed photon flux is:

$$F_{Photon} = G \cdot w \cdot t \cdot l$$

Dividing this into $i_d$ yields the photoconductive gain:

$$A_{Photoconductive} = \frac{i_d}{qF_{Photpn}} = \frac{qG\tau_{\text{min}}(\mu_e + \mu_h)\frac{w \cdot t}{l}v_{AB}}{qGwl} = \frac{\tau_{\text{min}}(\mu_e + \mu_h)v_{AB}}{l^2}$$

Noticing that the $l^2/(\mu_e + \mu_h)v_{AB}$ is the effective carrier transit time through the device, we see that the gain can be written as the minority carrier lifetime divided by the transit time through the device.

$$A_{Photoconductive} = \frac{\tau_{\text{min}}}{\tau_{\text{transit}}^*}$$

The gain is thus equivalent to the number of cycles a representative carrier makes through the device before it recombines.
An antique photoconductor at MIT:

The photoconductive light detector family contains some of the oldest semiconductor devices, some of the fastest optical devices, and some of the most advanced integrated optoelectronic ICs.

As an example of an old photoconductor, consider this antique:

A Stanley Magic Door with a lensed photoconductor-based sensor unit.

Do you know where it is on campus?
Interband vs. Intersubband

Interband
- Photon energy limited by the band gap
- Long lifetime ~1 ns

Intersubband
- Flexibility to adjust wavefunctions and energies
- Thermal stability of the operation wavelength
- Short lifetime ~1 ps
- Normal incidence radiation is not absorbed
Quantum well infrared photodetector (QWIP)

QWIPs operate on the principle of absorption by ISB transitions in QWs.

In the presence of an electric field the bands bend, allowing excited electrons to be swept out of the excited QW state and contribute to detected photocurrent.
Quantum Well Infrared Photodetector

- Very small bandgap materials (PbTe, PbSe, HgCdTe, $E_G \sim 0.1$ eV) are difficult to grow and process. Detectors are slow due to defects.
- GaAs QWIPs present the advantages of a mature technology ⇒ large area, high uniformity, excellent reproducibility.

Bound-to-bound operation

Bound-to-continuum operation
AlGaAs/GaAs QWIPs

![Graph showing responsivity vs wavelength for different samples A to F with parameters such as length, doping, and intersubband transitions.]

<table>
<thead>
<tr>
<th>Sample</th>
<th>$L_w$ (Å)</th>
<th>$L_b$ (Å)</th>
<th>$x$</th>
<th>$N_D$ (Å)</th>
<th>Doping Type</th>
<th>Periods</th>
<th>Intersubband Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>40</td>
<td>500</td>
<td>0.26</td>
<td>1.0</td>
<td>n</td>
<td>50</td>
<td>B-C</td>
</tr>
<tr>
<td>B</td>
<td>40</td>
<td>500</td>
<td>0.25</td>
<td>1.6</td>
<td>n</td>
<td>50</td>
<td>B-C</td>
</tr>
<tr>
<td>C</td>
<td>60</td>
<td>500</td>
<td>0.15</td>
<td>0.5</td>
<td>n</td>
<td>50</td>
<td>B-C</td>
</tr>
<tr>
<td>D</td>
<td>70</td>
<td>500</td>
<td>0.10</td>
<td>0.3</td>
<td>n</td>
<td>50</td>
<td>B-C</td>
</tr>
<tr>
<td>E</td>
<td>50</td>
<td>500</td>
<td>0.26</td>
<td>1.4</td>
<td>n</td>
<td>25</td>
<td>B-B</td>
</tr>
<tr>
<td>F</td>
<td>45</td>
<td>500</td>
<td>0.30</td>
<td>0.5</td>
<td>n</td>
<td>50</td>
<td>B-QB</td>
</tr>
</tbody>
</table>
Other ISB devices

- **Quantum fountain laser**
  - Fonstad/Palacios, 5/5/09

- **Quantum cascade laser**
  - Lecture 23 (Palacios insert) – Slide 17

- **Electro-optical modulator**

- **Quantum cascade laser**
  - $\tau_{\text{rec}} = 160-400 \text{ fs} @ 1.55 \mu\text{m}$

- **All-optical switch**

- **Mini-band injector**
  - **Active region**

- **1 period**
Interband vs. Intersubband

Interband Devices
- AlGaN
- AlGaAs
- InGaAs
- InAlAsSb
- GaSb
- Sels de Pb

Wavelength (μm)
- UV
- VIS
- NIR
- Mid-IR
- Far-IR

Frequency (THz)
- 1000
- 100
- 10
- 1

Intersubband Devices
- InGaAs/AlInAs/InP
- GaAs/AlGaAs
- InAs/AlSb
- GaN/AlN

Telecommunication wavelengths
Material choice

Discontinuity $\Delta E_C$ should be large

- Limits largest photon energy
- High temperature operation (carrier spillover)

Effective mass should be small

- Oscillator strength $\sim 1/m^*$
- Well width $\sim 1/m^*$ (roughness scattering)
- Strength of the optical phonon emission $\sim (1/m^*)^{1/2}$

Position of other band maxima

Availability of the technology
## Heterostructure materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Delta E_c$ (eV)</th>
<th>$m^*/m$</th>
<th>$\tau$ (ps)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAs/AlInAs</td>
<td>0.5</td>
<td>0.043</td>
<td>0.8</td>
<td>QWIP and QCL technologies established</td>
</tr>
<tr>
<td>GaAs/AlGaAs</td>
<td>0.3</td>
<td>0.067</td>
<td>0.65</td>
<td>QWIP technology established QCL demonstrated</td>
</tr>
<tr>
<td>Al(In)N/Ga(In)N</td>
<td>~1.8</td>
<td>0.2</td>
<td>0.2</td>
<td>Challenging material QWIP @ 1.55 $\mu$m demonstrated</td>
</tr>
<tr>
<td>SiGe</td>
<td>~0.25</td>
<td>0.2</td>
<td>~1</td>
<td>Holes: Si technology Low FiR loss</td>
</tr>
<tr>
<td>InGaAs/AlAsSb</td>
<td>&gt;2</td>
<td>0.023</td>
<td>1.2</td>
<td>Difficult material Maybe potential for 1.55 $\mu$m</td>
</tr>
</tbody>
</table>
**Photoconductors** - quantum well infrared photodetectors

**QWIPs**

Above: Schematic illustration of QWIP structure and function.

Right: Energy separation between \( n = 1 \) and \( 2 \) levels in quantum wells with indicated aluminum fractions and well widths.
Photoconductors - single-color QWIP imaging array

Ref: Lockheed-Martin (now BAE Systems), Nashua, N.H.
Photoconductors - two-color QWIP imaging array

Ref: Lockheed-Martin (now BAE Systems), Nashua, N.H.
Semiconductor Photodetectors - photodiodes, photoconductors, and photocapacitors

Photodiode: \( I(t) = a \times L(t) \)

Photoconductor: \( G(t) = a \times L(t) \)

Photocapacitor: \( Q(T) = a \times \int_{T}^{T} L(t) \, dt \)
Photodiodes - *illuminated p-n junction diodes*

Consider a p-n diode illuminated at \( x = x_n + a(w_n-x_n) \), \( 0 \leq a \leq 1 \).

What is \( i_D(v_{AB}, M) \)? Use superposition to find the answer:

\[
i_D(v_{AB}, M) = i_D(v_{AB}, 0) + i_D(0, M)
\]

We know \( i_D(v_{AB}, 0) \) already...

\[
i_D(v_{AB}, 0) = I_S(e^{qv_{AB}/kT} - 1)
\]

The question is, "What is \( i_D(0, M) \)."

\[
i_D(0, M) = ?
\]
Photodiodes - cont.: the photocurrent, $i_D(0,M)$

The excess minority carriers:

The minority carrier currents:

The photocurrent, $i_D(0,M)$:

$$i_D(0, M) = -A qM (1 - a)$$
Photodiodes - cont.: *The i-v characteristic and what it means.*

The total current:

$$i_D(v_{AB}, M) = i_D(v_{AB}, 0) + i_D(0, M)$$

$$= I_S e^{q v_{AB}/kT} - 1 - A q M (1 - a)$$

The illumination shifts the ideal diode curve vertically down.

Light detection in this quadrant

Power conversion in this quadrant
Semiconductor Photodetectors - bulk band-to-band absorption

- **Comparison of the absorption edge of several direct- and indirect-gap semiconductors**

Notice the abruptness of the absorption edge, and the difference in the strength of the absorption just above the band-edge.

\[ \alpha = 10^4 \text{ cm}^{-1} \Rightarrow 90\% \text{ absorbed in } \sim 2 \mu\text{m} \]

Singh Fig. 10.4
Photodiodes - cont.: the photocurrent, $i_D(0,M,x)$

The photocurrent, $i_D(0,M,a)$ vs $a$:

Replace contacts with reflecting boundaries:

Reflecting

$\delta m = x_n + a(w_n - x_n)$
Photodiodes - cont.: *the photocurrent, \( i_D(0,M) \)

The excess minority carriers:

\[
i_D(0,M) = -A q_M
\]

The minority carrier currents:

All of the photo-generated carriers cross the junction

\[
J_e(-w_p \leq x \leq -x_p) = 0
\]

\[
J_h(x_n \leq x \leq x_L = x_n + a(w_n - x_n)) = qM
\]
Photodiodes - cont.: the photocurrent, $i_D(0,M)$

Response with reflecting boundaries at each end:

How do we make reflecting boundaries and still make electrical contact?

And...isn't this easier on the top surface than on the bottom surface?

Does it matter? If so, when?
**Example:** an InGaAs cell with WBG InP reflecting "boundaries"

![Diagram of a solar cell structure]

- **p+ InP** 2E18 cm⁻³ 100 nm
- **p+ InGaAs** 2E18 cm⁻³ 0.3 µm
- **n InGaAs** 1E17 cm⁻³ 4 µm
- **n+ InP Substrate**

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Photodiodes - Near IR heterostructure p-i-n detectors

Left: Mesa-etched, front-illuminated InGaAs P-i-n with InAlAs window
Right: Mesa-etched, back-illuminated AlGaAs/GaAs P-i-N

Singh Figs. 10.13 (left) and 10.1.4 (right)
Photodiodes - GaN-based solar blind p-i-n detectors

**Left:** Layer structure used in solar-blind p-i-n photodiode

**Right:** Spectral response of GaN-based solar blind p-i-n photodiode structure pictured above

Photodiodes - avalanche photodiodes (APDs)

**Left:** Planar structure ion implanted guard ring; top-side input

**Right:** Back illuminated mesa-geometry. The sloped mesa side-walls eliminate edge breakdown

Fonstad/Palacios, 5/5/09

Lecture 23 - Slide 36
Photodiodes - avalanche photodiodes (APDs)

Above: Cross-section and concept

Right: Performance compared to other devices: top - photo response, and - bottom - excess noise factors

Photodiodes - avalanche photodiodes (APDs)

Photoconductors: Conclusions

😊 Easy to fabricate

😊 High responsivity (high gain)

😊 Slow

😊 Non-linear response

😊 Noisy

😊 Very sensitive to the presence of defects in the material
p-i-n photodiode

- In principle, no gain (see Avalanche Photodiodes)
- Very low capacitance ⇒ The time response can be limited by the carrier transit time
- Shot noise is dominant (scales linearly with the dark current) but very low leakage are expectable
- Excellent solution when doping is well controlled
Avalanche Photodiodes

The impact-ionization mechanism

- Large gain (~200) possible
- Significant enhancement of shot noise due to avalanche multiplication
- New noise source associated to fluctuations in the multiplication gain
Schottky photodiode

- No gain
- Responsivity limited by transmission through the Schottky contact
- Time response typically limited by the capacitance of the device (scales linearly with the surface and decreases with reverse bias)
- Shot noise is dominant (scales linearly with the dark current)
- In general excellent performance, particularly for high energy detection
Metal-semiconductor-metal photodiodes

- Planar devices. Two Shottky contacts
- Fast: Driven in the transit time limit. Drift transport
- Low dark current
- Easy to fabricate and integrate
- Low responsivity, limited by the surface of the contacts
Photovoltaic Energy Conversion: Solar cells and TPV

Fourth quadrant operation: $v_{AB}i_D < 0$

Efficiency issues:
1. $h\nu$: $E_g$ mismatch
2. $V_{oc}$ and fill factor
3. Intensity (concentrator) effect

$$i_D(v_{AB}, L) = I_S \left( e^{qv_{AB}/kT} - 1 \right) - q\eta_i L$$
Photovoltaic Energy Conversion: Solar cells and TPV, cont.

**Efficiency issues:**

1. \( h \nu \): \( E_g \) mismatch
2. \( V_{oc} \) and fill factor
3. Intensity (concentrator) effect

1. \( h \nu \)
   \[
   \begin{cases} 
   < E_g & \text{not absorbed; energy lost} \\
   > E_g & \text{excess energy, } (h \nu - E_g), \text{ lost} 
   \end{cases}
   \]

2. \( V_{oc} = \frac{kT}{q} \ln \left( \frac{q \eta_i L}{I_S} \right) \)
   \[ P_{out \ max} < -i_{sc} V_{oc} = \eta_i L \cdot kT \ln \left( \frac{q \eta_i L}{I_S} \right) \]

3. \( L \uparrow \Rightarrow \eta \uparrow \)

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Skyline Solar parabolic reflector/concentrator multi-junction cell installation photo-illustration from website.
Concentrator installations

Multi-junction cells - efficiency improvement with number

“Photovoltaics take a load off soldiers,” Oct. 27, 2006, online at: http://compoundsemiconductor.net/cws/article/magazine/26146
Multi-junction cells, cont. - 2 designs

<table>
<thead>
<tr>
<th>InGaP cell</th>
<th>$E_g = 1.84$ eV (0.67 µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel junction</td>
<td></td>
</tr>
<tr>
<td>GaAs cell</td>
<td>$E_g = 1.43$ eV (0.86 µm)</td>
</tr>
<tr>
<td>Tunnel junction</td>
<td></td>
</tr>
<tr>
<td>Ge cell</td>
<td>$E_g = 0.7$ eV (1.75 µm)</td>
</tr>
<tr>
<td>Substrate</td>
<td></td>
</tr>
<tr>
<td>Ge or GaAs</td>
<td></td>
</tr>
</tbody>
</table>

**A 3-junction design**
(3 lattice-matched cells connected in series by tunnel diodes)

**A 6-junction design**
(3-tandem multi-junction cells set side-by-side)

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* "Photovoltaics take a load off soldiers," Oct. 27, 2006, online at: http://compoundsemiconductor.net/cws/article/magazine/26146
Multi-junction cells, cont. -

Side-by-side, lateral placement of cells, instead of 3-d stacking*

"Photovoltaics take a load off soldiers," Oct. 27, 2006, online at: http://compoundsemiconductor.net/cws/article/magazine/26146
Multi-junction cells, cont. -

<table>
<thead>
<tr>
<th>six-junction solar-cell bandgaps</th>
<th>six-junction solar cell at 20X</th>
<th>100X</th>
</tr>
</thead>
<tbody>
<tr>
<td>high $E_g$ 2.4 eV</td>
<td>thermodynamic efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14.9%</td>
<td>13.8%</td>
</tr>
<tr>
<td>GalnP 1.84 eV</td>
<td>practical efficiency limit</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16.6%</td>
<td>14.3%</td>
</tr>
<tr>
<td>GaAs 1.43 eV</td>
<td>derating of thermodynamic efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13.9%</td>
<td>11.7%</td>
</tr>
<tr>
<td>Si 1.12 eV</td>
<td>total</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\eta = 64.2%$</td>
<td></td>
</tr>
<tr>
<td>0.95 eV</td>
<td>total</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\eta = 54.3%$</td>
<td></td>
</tr>
<tr>
<td>0.70 eV</td>
<td>total</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\eta = 55.6%$</td>
<td></td>
</tr>
</tbody>
</table>

Efficiency analysis w. and w.o. concentration vs thermodynamic max*  

* "Photovoltaics take a load off soldiers," Oct. 27, 2006, online at: http://compoundsemiconductor.net/cws/article/magazine/26146
Multi-junction cells, cont. - current reality, recent records

NREL 8/08*: 40.8% at 326 suns
A metamorphic cell grown in inverted order on GaAs, followed by substrate removal. (NREL says they are working toward an optimal cell with a 1.85 eV top cell and 0.93 eV bottom cell, as well as on an optimized 4-junction cell.)

Fraunhofer ISE 1/09**: 41.1% at 454x
Metamorphic (similar to NREL structure) but on Ge

---

InGaP cell
$E_g = 1.83$ eV (0.67 $\mu$m)
- tunnel junction
- transparent grade

Ga$_{0.96}$In$_{0.04}$As cell
$E_g = 1.34$ eV (0.92 $\mu$m)
- tunnel junction
- transparent grade

Ga$_{0.63}$In$_{0.37}$As cell
$E_g = 0.89$ eV (1.39 $\mu$m)
- contact

Mechanical handle

---

* http://compoundsemiconductor.net/cws/article/news/35420
** Press release: www.ise.fraunhofer.de
**Thermo-photovoltaics (TPV)**

"Solar cells" for cooler blackbodies

\[ \lambda_{pk} = \left(2.898 \times 10^6 \text{ nm} \cdot \text{K} \right)/T \]

\[ P_{Tot} = \left(5.67 \times 10^{-8} \text{ W m}^{-2} \text{K}^{-4} \right) \cdot T^4 \]

Si cells, 2000 K BB

1 - 2% eff

Thermo-photovoltaic (TPV) Converter
System schematic

Input
Heat
Energy

Radiator
Filter
TPV Cell(s)
Reflector

Electrical
Energy
Output

Key: Useable radiation
Non-usable rad.
TPV Applications

Note: These two examples burn fuel to generate heat, but the greatest interest in TPV is to utilize "waste" heat that is typically not used... a car's exhaust and the waste heat from an ovens and industrial furnaces, for example.

Photonic Crystal Emitters - 1-d for TPV systems

**Photonic Crystal Emitters** - 3-d for TPV systems

A stacked log 3-d photonic crystal made of tungsten by a modified Si process.

Photonic Crystal Emitters - 3-d for TPV systems

Comparing several emitting surfaces used with a GaSb TPV cell: a black body (BB), an $\text{Er}_2\text{O}_3$ surface (Er-Oxide), structured tungsten (Stru.-W), and a 3-d photonic crystal.

Evolution of TPV to MTPV

Standard TPV geometry
Radiation and cell widely separated

Initial MTPV
Submicron gap between radiator and cell

Back contact MTPV
Junction on side away from hot radiator
Microscale Thermophotovoltaic Energy Conversion

A classical physics experiment demonstrating large evanescent coupling between two closely space dielectric prisms

Prisms apart; no transmission

Prisms in close proximity; large transmission
Proximity Enhancement of Thermophotovoltaic Energy Conversion

$n_{BB} = 3.3, \ 320 \text{ K} < T_{BB} < 770 \text{ K}$

Approximate cell output at large separation, $L$

<table>
<thead>
<tr>
<th>Blackbody $T$</th>
<th>2.5 $\mu$m Cell</th>
<th>3.6 $\mu$m Cell</th>
<th>5 $\mu$m Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>320 K (50°C):</td>
<td>1 $\mu$W/cm$^2$</td>
<td>84 $\mu$W/cm$^2$</td>
<td>1 mW/cm$^2$</td>
</tr>
<tr>
<td>470 K (200°C)</td>
<td>0.5 mW/cm$^2$</td>
<td>7 mW/cm$^2$</td>
<td>30 mW/cm$^2$</td>
</tr>
<tr>
<td>620 K (350°C)</td>
<td>12.5 mW/cm$^2$</td>
<td>75 mW/cm$^2$</td>
<td>200 mW/cm$^2$</td>
</tr>
<tr>
<td>770 K (500°C)</td>
<td>100 mW/cm$^2$</td>
<td>350 mW/cm$^2$</td>
<td>650 mW/cm$^2$</td>
</tr>
</tbody>
</table>

NOTE: Vertical bars indicate the range of the increase: Upper end - 320 K
Lower end - 770 K
Modulators - based on waveguide couplers

Applying electric fields to the waveguides changes their effective indices through the electro-optic effect and thus changes the amount of transfer from one guide to the other, making a switch or modulator.

In the lower structure the sign of the field is switched mid-way along the coupler. It can be shown that this results in better control over the switching.

Source: H. P. Zappe, Introduction to Semiconductor Integrated Optics (Artech House, Norwood, MA, 1995) Fig. 11.1.
Modulators - based on Mach-Zehnder interferometer

When a light beam is split, sent through two different paths, and then recombined we create what is known as a Mach-Zehnder interferometer.

If the path lengths are identical, the beams will add constructively and the resulting intensity will be the same as the initial intensity.

If the path lengths differ, the beams will interfere destructively, and the intensity will be reduced accordingly.

Source: H. P. Zappe, Introduction to Semiconductor Integrated Optics (Artech House, Norwood, MA, 1995) Fig. 11.10.
**Modulators** - multi-quantum well structures

Using the quantum-confined Stark effect

Quantum well band edge profile with and without an applied field, and the corresponding changes in the absorption edge and index.

Modulators - multi-quantum well structures, cont.

Data illustrating the improved characteristics obtained from MQW modulator structures employing multiple coupled quantum well units instead of multiple single (i.e., isolated) wells.

Ref: J. Trezza, et al., in Heterogeneous Optoelectronics Integration, Fonstad/Palacios, 5/5/09. D. Towe, ed. (SPIE Press, Bellingham, WA, 2000) Fig. 5.28, p. 207. Lecture 23 - Slide 64
**Modulators** - multi-quantum well structures, cont.

A tabulation of some of the many combinations of MQW sections, mirror structures, and operating wavelengths that can be used to achieve various types of devices and modes of operation. Note that the same device can be operated at zero, forward, and reverse bias, and can exhibit a variety of behaviors. For most modulator applications one is concerned only with zero and reverse biases.

Ref: J. Trezza, et al., in *Heterogeneous Optoelectronics Integration*, E. Towe, ed. (SPIE Press, Bellingham, WA, 2000), Fig. 5.29, p 208.
Modulators - multi-quantum well structures, cont.

Multi-quantum well (MQW) modulator operating with light input in the plane of the wells.

MQW modulators are more commonly used with light input normal to the plane of the wells, so this is a useful reminder that in-plane operation is also possible.

Source: H. P. Zappe, Introduction to Semiconductor Integrated Optics (Artech House, Norwood, MA, 1995) Fig. 11.8.
Modulators - Silicon MOS-based Mach-Zehnder (Intel)

SEM cross-section

Mode overlap with inversion layer

Eye diagram at 10 Gbps

Full layout showing multiple taps to allow adjustment of the modulator

**Modulators** - Silicon p-n junction based modulator (Cornell)

Cross-section and layout. Carriers are injected into the intrinsic region of a p-i-n structure to modulate the refractive index and resonance.


Photomicrographs

Resonance shift with forward bias voltage
**Modulators** - Silicon p-n junction based WDM modulator (Cornell)

Eye diagram at 4 Gbps

Schematic of layout

Photomicrograph showing two rings

Waveform and resonance shift

**Modulators** - InP p-n junction based ring modulator (USC)

Photomicrograph (above) and cross-section (below)

Layer structure used

Eye diagram at 10 Gbps