Astronomical Observing Techniques

Lecture 9: Silicon Eyes 1

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Overview

1. Solid State Physics
2. Intrinsic Photoconductors
3. Extrinsic Photoconductors
4. Readout & Operations
5. Detector Noise
Modern Detectors

1. Photon detectors
   Respond directly to individual photons -> releases bound charge carriers.
   Used from X-ray to infrared.
   Examples: photoconductors, photodiodes, photoemissive detectors

2. Thermal detectors
   Absorb photons and thermalize their energy -> changes resistance ->
   modulates electrical current. Used mainly in IR and sub-mm detectors.
   Examples: bolometers

3. Coherent receivers
   Respond directly to electrical field and preserve phase information (but
   need a reference phase “local oscillator”). Mainly used in the sub-mm
   and radio regime.
   Examples: heterodyne receivers
## Periodic Table of the Elements

### Periodic Table Details
- **Relative Atomic Mass (1)**: Represents the mass of an atom relative to the mass of a carbon atom.
- **Metal**: Elements in the left side of the periodic table.
- **Nonmetal**: Elements on the right side of the periodic table.
- **Semi-metal**: Elements in the middle of the periodic table.
- **Group**: Arranged in columns, with Groups 1A (IA) being the far left and 18A (VIII) being the far right.
- **Period**: Arranged in rows, with the first period having 2 elements and the last period having 18 elements.

### Standard State (25 °C; 101 kPa)
- **Ne**: gas
- **Fe**: solid
- **Ga**: liquid
- **Te**: synthetic

### Elements Listed
- **Group 1A (IA)**: Hydrogen (H)
- **Group 2A (IIA)**: Lithium (Li), Be, B, and Boron (B)
- **Group 3A (IIIA)**: Sodium (Na), Magnesium (Mg), Alkaline earth metals
- **Group 4A (IVA)**: Potassium (K), Ca, Sc, Ti, Vanadium (V), Chromium (Cr), Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni), Copper (Cu), Zinc (Zn)
- **Group 5A (VA)**: Gallium (Ga), As, Se, Br, and Krypton (Kr)
- **Group 6A (VIA)**: Rubidium (Rb), Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, Indium (In), Sn, Sb, Te, I, and Tellurium (Te)
- **Group 7A (VIIA)**: Cesium (Cs), Ba, La, Lu, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn

### Additional Notes
- **Lanthanide**: Elements with atomic numbers 57 to 71.
- **Actinide**: Elements with atomic numbers 89 to 103.

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*Note: The periodic table is a visual representation of the elements, showing their atomic numbers, symbols, and relative positions in the periodic system.*
Diamond Lattice

- Elements with 4 e\(^-\) in valence shell form crystals with **diamond lattice structure** (each atom bonds to four neighbors).
- These double-bonds between neighbours are due to “shared” electrons.
Diamond Lattice

Diamond lattice not only formed by group IV elements (C, Si, Ge) but also by III-V semiconductors (InSb, GaAs, AlP)
Electronic States and Bands

Single atomic system

Example: H atom

Atomic crystal

Wavefunctions $\Psi$ overlap

$\rightarrow$ Energy levels of individual atoms split due to Pauli principle (avoiding the same quantum states)

$\rightarrow$ Multiple splitting $\rightarrow$ “bands”
Fermi Energy

- **Fermi energy** $E_F$ determines concentration of thermally excited electrons in conduction band
- Energy valence band: $E_V$; Energy conduction band: $E_C$
- Fermi function $f(E)$: probability that state of energy $E$ is occupied at temperature $T$.

\[
n_0 = N_c f(E_c), \quad N_c = 2 \left( \frac{2\pi m_{\text{eff}} kT}{\hbar^2} \right)^{3/2}
\]

\[
f(E_c) = \frac{1}{1 + e^{(E_c - E_F)/kT}} \approx e^{-(E_c - E_F)/kT}
\]
**Fermi energy** = energy of the highest occupied quantum state in a system of fermions at $T=0K$

QM: fermions obey the **Pauli exclusion principle** → two fermions cannot occupy the same quantum state. Fermions consecutively fill up the unoccupied quantum states starting with the lowest energy; when all the particles have been put in, the Fermi energy is the energy of the highest occupied state.

**Fermi level** = chemical potential

The Fermi level is the energy at which there is a 50% chance of finding an occupied energy state. The Fermi level can be calculated from the density of states in the conduction and valence bands. The Fermi level may increase, remain the same or decrease with increasing temperature, depending on the number of states in the conduction and valence bands.

Fermi energy and Fermi level are only the same at absolute zero. At absolute zero temperature the Fermi level can be thought of as the energy up to which available electron states are occupied. At higher temperatures, the Fermi level is the energy at which the probability of a state being occupied has fallen to 0.5.

The **Fermi function** $f(E)$ gives the probability that a given available electron energy state will be occupied at a given temperature. Typically, most of the levels up to the Fermi level $E_F$ are filled, and relatively few electrons have energies above the Fermi level.

The population of states depends upon the *product* of the Fermi function and the electron density of states:

- In the gap there are no electrons because the density of states is zero.
- In the conduction band at $0K$, there are no electrons even though there are plenty of available states, but the Fermi function is zero.
- At high temperatures, both the density of states and the Fermi function have finite values in the conduction band, so there is a finite conducting population.
Electric Conductivity

Conductivity requires charge carriers in the conduction band.

Overcome bandgap $E_g$ to lift $e^-$ into conduction band:

1. external excitation, e.g. via a photon $\leftarrow$ photon detector
2. thermal excitation
3. impurities
Intrinsic Photo-Conductors: Basic Principle

- semi-conductor: few charge carriers $\rightarrow$ high resistance
- charge carriers = electron-hole pairs
- photon lifts $e^-$ into conduction band
- applied electric field drives charges to electrodes
Photo-Current

- Conductivity: \( j = \sigma E \)
- Current: \( I = j w d \)
- \( V = R I, \ E = V / l \)

\[
\sigma = \frac{1}{R_d} \frac{l}{wd} = q n_0 \mu_n
\]

where:
- \( R_d \) = resistance
- \( w, d, l \) = geometric dimensions
- \( q \) = elementary electric charge
- \( n_0 \) = number density of charge carriers
- \( \phi \) = photon flux
- \( \eta \) = quantum efficiency
- \( \tau \) = mean lifetime before recombination
- \( \mu_n \) = electron mobility \( \sim \) mean time between collisions.

Drift velocity \( v = \mu_n E \), current density \( j = n_0 q v \)
Important Quantities and Definitions

Quantum efficiency \( \eta \) = \( \frac{\text{# absorbed photons}}{\text{# incoming photons}} \)

Responsivity \( S \) = \( \frac{\text{electrical output signal}}{\text{input photon power}} \)

Wavelength cutoff: \( \lambda_c = \frac{hc}{E_g} = 1.24 \mu m \)

Photo-current: \( I_{ph} = q \varphi \eta G \)

Photoconductive gain \( G \): \( G = \frac{I_{ph}}{q \varphi \eta} = \frac{\tau}{\tau_t} = \frac{\text{carrier lifetime}}{\text{transit time}} \)

The product \( \eta G \) describes the probability that an incoming photon will produce an electric charge that will reach an electrode.
Limitations of Intrinsic Semiconductors

• long-wavelength cutoffs

\[ \lambda_c = \frac{hc}{E_g} \]

→ Germanium: 1.85µm
→ Silicon: 1.12µm
→ GaAs: 0.87µm

• non-uniformity of material

• problems to make good electrical contacts to pure Si

• difficult to avoid impurities and minimize thermal (Johnson) noise
Extrinsic Semiconductors

- extrinsic semiconductors: charge carriers = electrons (n-type) or holes (p-type)
- achieved by addition of impurities at low concentration to provide excess electrons or holes

→ much reduced bandgap -> longer wavelength cutoff

Example: addition of boron to silicon in the ratio 1:100,000 increases its conductivity by a factor of 1000!
## Extrinsic Semiconductor Band Gaps

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Type</th>
<th>Ge Cutoff wavelength $\lambda_c$ ($\mu$m)</th>
<th>Si Cutoff wavelength $\lambda_c$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>p</td>
<td>$119^b$</td>
<td>$18.5^a$</td>
</tr>
<tr>
<td>B</td>
<td>p</td>
<td>$52^b$</td>
<td>$28^a$</td>
</tr>
<tr>
<td>Be</td>
<td>p</td>
<td>$115^b$</td>
<td>$8.3^a$</td>
</tr>
<tr>
<td>Ga</td>
<td>p</td>
<td>$111^b$</td>
<td>$17.2^a$</td>
</tr>
<tr>
<td>In</td>
<td>p</td>
<td>$98^b$</td>
<td>$7.9^a$</td>
</tr>
<tr>
<td>As</td>
<td>n</td>
<td>$31^b$</td>
<td>$23^a$</td>
</tr>
<tr>
<td>Cu</td>
<td>p</td>
<td>$103^b$</td>
<td>$5.2^a$</td>
</tr>
<tr>
<td>P</td>
<td>n</td>
<td>$129^b$</td>
<td>$27^a$</td>
</tr>
<tr>
<td>Sb</td>
<td>n</td>
<td></td>
<td>$29^a$</td>
</tr>
</tbody>
</table>

**Problem:** absorption coefficients much less than for intrinsic photoconductors $\rightarrow$ low QE $\rightarrow$ active volumes (pixels) must be large
Blocked Impurity Band (BIB) Detectors

Solution: use separate layers to optimize the optical and electrical properties independently:

- **IR-active layer**: heavily doped
- **Blocking layer**: thin layer of high purity (intrinsic photoconductor)
- **Typical species are Si:As or Si:Sb BIBs**
Photodiodes

- junction between *two* oppositely doped zones
- Two adjacent zones create a *depletion region* with high impedance

1. Photon gets absorbed e.g. in the p-type part
2. Absorption creates an e⁻-hole pair
3. The e⁻ diffuses through the material
4. Voltage drives the e⁻ across the depletion region $\rightarrow$ photo-current

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Charge Coupled Devices (CCDs)

CCDs = array of integrating capacitors.
Pixel structure: metal “gate” evaporated onto SiO₂ (isolator) on silicon = MOS

1. photons create free e⁻ in the photoconductor
2. e⁻ drift toward the electrode but cannot penetrate the SiO₂ layer
3. e⁻ accumulate at the Si—SiO₂ interface
4. total charge collected at interface measures number of photons during the exposure
5. → read out the number of e⁻
Charge Coupled Readouts

Collected charges are passed along the columns to the edge of the array to the output amplifier.

Be aware of charge transfer (in-)efficiencies (CTEs) due to electrostatic repulsion, thermal diffusion and fringing fields.
Charge Transfer Efficiency (CTE)

Time-dependent mechanisms that influence the CTE:

1. **Electrostatic repulsion** causes electrons to drift to the neighbouring electrode with time constant for charge transfer $\tau_{SI}$.

2. **Thermal diffusion** drives electrons across the storage well at $\tau_{th}$.

3. “**Fringing fields**” due to dependency of the well on the voltages of neighbouring electrodes ($\tau_{ff}$).

Approximation for the CTE of a CCD with $m$ phases:

$$CTE = \left(1 - e^{-t/\tau}\right)^m$$

Noise from **charge transfer inefficiency**: $\varepsilon = (1 - \text{CTE})$
CCD Color Sensors

1. Take three exposures through three filters subsequently – only works for fixed targets (standard for astronomy).
2. Split the input beam in three channels, each with a separate and optimized CCD (professional video cameras).
3. Bayer mask over CCD – each subset of 4 pixels has one filtered red, one blue, and two green.
Main Detector Noise Components

**G-R noise**
\[
\langle I_{G-R}^2 \rangle = 4q^2 \varphi \eta G^2 \Delta f
\]

Fundamental statistical noise due to the Poisson statistics of the photon arrival transferred into the statistics of the generated and recombined holes and electrons.

**Johnson or kTC noise**
\[
\langle I_J^2 \rangle = \frac{4kT}{R} \Delta f
\]

Fundamental thermodynamic noise due to the thermal motion of the charge carriers. Consider a photo-conductor as an RC circuit. Since \(\langle Q^2 \rangle = kTC\), the charge noise is also called kTC noise or reset noise.

**1/f noise**
\[
\langle I_{1/f}^2 \rangle \propto \frac{I^2}{f} \Delta f
\]

Increased noise at low frequencies, due to bad electrical contacts, temperature fluctuations, surface effects (damage), crystal defects, and JFETs, ...

The total noise in the system is:
\[
\langle I_N^2 \rangle = \langle I_{G-R}^2 \rangle + \langle I_J^2 \rangle + \langle I_{1/f}^2 \rangle
\]
BLIP and NEP

Operationally, **background-limited performance (BLIP)** is always preferred:

\[
\langle I_{G-R}^2 \rangle \gg \langle I_J^2 \rangle + \langle I_{1/f}^2 \rangle
\]

The noise equivalent power (NEP) is the signal power that yields an RMS S/N of unity in a system of \(\Delta f = 1\) Hz:

\[
NEP_{G-R} = \frac{2hc}{\lambda} \left( \frac{\varphi}{\eta} \right)^{1/2}
\]

In BLIP the NEP can only be improved by increasing the quantum efficiency \(\eta\).