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1. Semiconductor Fundamentals

1(a) Electron vs Hole Mobility

Electrons generally have higher mobility because in a semiconductor's conduction band, they behave as lighter, less interacting particles. Holes, in the valence band, occupy states with greater effective masses and scatter more, so their mobility is lower.

1(b) Dependence of Mobility on Doping

As doping concentration increases, impurity scattering becomes more frequent—free carriers collide more often with dopant ions. Thus, **higher doping → lower mobility**. Mobility μ typically decreases roughly with $N^{-1/3}$ to $N^{-2/3}$ at moderate-to-high doping levels.

1(c) Doping Profiles – Abrupt vs Linear

```
Abrupt:       ┌────────── NA ─────────┐
          |         |
------------------------------------- x
          |         |
           └────────── ND ─────────┘
```

Linearly-graded:

```
         /
        /
       /
     /
    /
--------------------------------- x
```

- **Abrupt junction** features a steep step change in doping across the interface.
- **Linearly graded** junction shows a gradual, straight-line doping change.

1(d) Energy-Band Diagrams at Thermal Equilibrium

```
p-type:        Ec   ◀——— E_v
            ■↑
     EF closer to Ev

n-type:        Ec
            ↑■  |
              └—EF closer to Ec

p-n junction:  Ev |        Ec
            \       /
             \     /
         EF —┼———————————┼—— constant across both
```

- In **p-type**, EF lies nearer to Ev.
- In **n-type**, EF lies nearer to Ec.
- In a **p-n junction**, EF is constant in equilibrium, and bands bend across the depletion region.

1(e) n–p–n Transistor – Doping Profile & Symbol

Doping Profile:

Emitter (n^+) ─┃────────── (p) ─┃──────── (n)
Base Collector

Symbol:

```
   C
   |
  /\
 | ▲ |── E
  \/
   |
   B
```

Arrow on emitter points out (n → p).

1(f) Schematic – n-Channel MOSFET

```
 G
 |
 ┌──┴──┐
|   |
S────┼────D
    |
   body (p-type substrate, often tied to source)
```

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2. Advanced Carrier Physics

2(a) Rest Mass vs Effective Mass

- **Rest mass (m_0)** is the invariant mass of an electron in free space.
- *Effective mass (m)** accounts for the interaction with the semiconductor lattice: it's derived from the curvature of the **E–k relation**:

$$\frac{1}{m^*} = \frac{1}{\hbar^2}\frac{d^2E}{dk^2}$$

A sharper curvature → smaller m*, meaning carriers accelerate more under applied forces.

(Diagram: plot of E vs k showing different curvatures)

2(b) Electron Density in Intrinsic Semiconductor

- **Intrinsic density**:

$$n_i = \sqrt{N_C N_V} \exp\left(-\frac{E_g}{2kT}\right)$$

- **With Phosphorus doping (n-type)**: donor atoms contribute electrons, so total electron density increases to roughly the donor concentration:

$$n \approx N_D$$

and the hole density falls accordingly via mass action: $pn = n_i^2$.

2(c) Band-Gap Energy Calculation

Use: $E_g = 2kT \ln\left(\frac{\sqrt{N_C N_V}}{n_i}\right)$.

1. **At 300 K**: $kT = 0.026eV$, $\sqrt{N_C N_V} \approx \sqrt{2.86 \times 10^{19} \times 2.66 \times 10^{19}} \approx 2.76 \times 10^{19}$

$$E_g = 2 \times 0.026 \times \ln(2.76 \times 10^{19}/9.65 \times 10^9) \approx 1.12eV$$

2. **At 600 K**: $kT = 0.052eV$, masses and densities shift with T, but assuming same Nc, Nv:

$$E_g(600K) = 2 \times 0.052 \times \ln(2.76 \times 10^{19}/n_i(600K))$$

But n_n at 600 K will increase, making the logarithmic term drop—so E_g appears lower. More importantly, **actual** Eg shrinks with increasing T (Si Eg ~1.12 eV → ~1.08 eV at 600 K).

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3. Drift, Resistivity & Hall Effect

3(a) Carrier Drift & Resistivity

- Under electric field (E), carriers drift with velocity: $v_d = \mu E$.
- Current density: $J = q(n\mu_n + p\mu_p)E$.
- Resistivity ρ:

$$\rho = \frac{E}{J} = \frac{1}{q(n\mu_n + p\mu_p)}$$

3(b) Resistivity Measurement Methods

- **Four-point probe**: eliminates contact resistance; current flows through outer probes, voltage measured by inner.
- **Van der Pauw**: for arbitrary shape – measures resistivity via edge contacts.
- **Two-point probing**: simplest but error-prone due to contact resistance.

(diagrams: probe placements, wiring, sample shapes)

3(c) Hall Coefficient and Voltage Calculation

Given: $\mu = 1300 cm^2/V \cdot s$, $\rho = 0.048\Omega \cdot cm$. → Conductivity $\sigma = 1/\rho \approx 20.83\,\Omega^{-1} \cdot cm^{-1}$. → Carrier concentration $n = \sigma/(q\mu) \approx \frac{20.83}{1.6\times10^{-19}\times1300} \approx 1 \times 10^{17}\ cm^{-3}$.

- **Hall coefficient**: $R_H = -\frac{1}{qn} \approx -6.25 \times 10^{-4} cm^3/C$.

Sample dimensions: width $w = 500\mu m = 5 \times 10^{-2}\ cm$, area $A = 2.5 \times 10^{-3}\ cm^2$.

- Current $I = 1mA$.
- Magnetic field $B = 10^{-4}\ Wb/m^2 = 10^{-4}\ T$.

Hall voltage:

$$V_H = R_H \frac{IB}{t} = -6.25 \times 10^{-4} \frac{1 \times 10^{-3} \times 10^{-4}}{5 \times 10^{-2}}$$
$$\approx -1.25 \times 10^{-6}\ V$$

So: $R_H \approx -6.3 \times 10^{-4}\ cm^3/C$, $V_H \approx -1.3\mu V$.

4. Abrupt p–n Junction Analysis

4(a) Charge, Field & Potential Along Depletion

- **Charge density**: constant negative on p side, constant positive on n side, zero elsewhere.

- **Electric field (E)**: triangular, peaking at the metallurgical junction, linearly decaying to zero at edges.
- **Potential (φ)**: rises across the depletion zone to reach built-in potential (φ_i), flat (no E) outside.

4(b) Fermi Level Uniformity

Yes — in thermal equilibrium, there is a **single, constant Fermi level EF** across the junction even though the band edges shift (band bending).

4(c) Built-In Potential & Depletion Width Calculation

With Si, $n_i = 1.5 \times 10^{10}\ cm^{-3}$, $N_A = 2.5 \times 10^{15}\ cm^{-3}$, assume $N_D \gg N_A$:

Built-in potential:

$$\varphi_i = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

If $N_D \gg N_A$, then $\varphi_i \approx \frac{0.026}{1} \ln\left(\frac{2.5\times10^{15} N_D}{(1.5\times10^{10})^2}\right)$. Result will be ~~0.7 V (typical). Depletion width:

$$W = \sqrt{\frac{2\varepsilon_s \varphi_i (1/N_A + 1/N_D)}{q}}$$

Use $\varepsilon_s = 11.7\varepsilon_0$, plug in values, you get W around 1–2 μm.

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5. Breakdown & Varactor Behavior

5(a) Breakdown Mechanisms

3. **Zener breakdown**: in heavily doped (narrow depletion) junctions, high E-field allows tunneling near 5–6 V.
4. **Avalanche breakdown**: in lightly doped junctions, carriers gain enough energy to ionize atoms, causing multiplication—occurs at higher voltages (tens to hundreds of volts).

5(b) Varactor Diode Capacitance

- Capacitance:

$$C_j = \frac{\varepsilon A}{W}$$

- **Abrupt junction**: $C \propto (V_R + \varphi_i)^{-1/2}$.
- **Linearly graded junction**: $C \propto (V_R + \varphi_i)^{-1/3}$. With increasing reverse bias V_R, depletion width W grows, reducing C more sharply in abrupt junctions than in graded ones.

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6. Bipolar Junction Transistor (BJT)

6(a) Common-Base I–V Characteristics & Early Effect

- *Input curve (base-emitter)*: forward-bias exponential;
- *Output curve (collector-current vs collector-emitter voltage)*: flat 'active region' region; as V_{CE} rises, collector current rises slightly (Early effect), due to base-width narrowing.
- **Early effect**: finite slope in output curves; extrapolation intercept at Early voltage, V_A.

6(b) Transistor Current Parameters

Given currents: $I_{Ep} = 2.5mA, I_{En} = 0.005mA\ I_{Cp} = 2.495mA, I_{Cn} = 0.001mA$

- **Emitter efficiency** $\gamma = \frac{I_{Ep}}{I_{Ep}+I_{En}} = \frac{2.5}{2.505} \approx 0.998.$
- **Base transport factor** $\alpha_T = \frac{I_{Cp}}{I_{Ep}} = \frac{2.495}{2.5} \approx 0.998.$
- **Common-base current gain** $\alpha_0 = \gamma\alpha_T = 0.996.$
- **Leakage current** $I_{Cn0} = I_{Cn} = 0.001mA.$

6(c) BJT Energy-Band Diagrams

Thermal equilibrium: p–n–p regions aligned, Fermi level flat, bands step across emitter-base and base-collector junctions.

Active mode: emitter-base forward biased → bands lower; base–collector reverse biased → bands higher; result in electron injection and current flow, barrier asymmetry enabling controlled amplification.

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7. Field-Effect Devices & TRIAC/DIAC

7(a) JFET Structure & Key Voltages

- **Structure**: n-type channel with p-type gates on both sides.
- **Pinch-off Voltage** V_P: gate voltage where channel closes and drain current saturates.
- **Saturation Voltage**: drain-to-source voltage beyond which channel pinch-off occurs; current flattens.

7(b) MOSFET Modes

- **Depletion-mode MOSFET**: channel exists at V_G=0; you can deplete it by applying negative V_G.
- **Enhancement-mode MOSFET**: no channel at V_G=0; channel forms only when V_G exceeds threshold. *Schematics and I–V curves reflect these differences.*

7(c) DIAC vs TRIAC

Feature	DIAC	TRIAC
Structure	Two-terminal, bidirectional switch	Three-terminal, bidirectional switching device
Triggering	Fires at breakover voltage	Gate-controlled switching
Use cases	Trigger device for TRIAC	AC power control (light dimmers, motor speed)
Characteristics	No gate terminal	Gate allows controlled firing and phase control

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That's a comprehensive overview. Let me know if you'd like step-by-step derivations, numerical walkthroughs, or clean diagrams for any part!