Appendix A

Symbols and Acronyms

List of symbols used in text.

a	lattice constant
a_0	Bohr radius
$\mathbf{a}$	acceleration
$\mathbf{a}_x, \mathbf{a}_y, \mathbf{a}_z$	rectangular coordinate unit vectors
$\mathbf{B}$	magnetic flux density
c	speed of light in vacuum
C	capacitance
e	proton charge
$\mathbf{E}$	electric field intensity
$\mathcal{E}$	electric field magnitude
E	energy
E_F	Fermi energy
E_g	gap energy
E_c	conduction bandedge energy (or charging energy)
E_v	valence bandedge energy
$\mathbf{F}$	force
f	frequency
G	conductance
h	Planck's constant
$\hbar$	Planck's reduced constant
H	Hamiltonian
H_n	Hermite polynomials
i	imaginary unit
I	current (or optical intensity)
$\mathbf{J}$	current density
$\mathbf{k}$, k	wavevector, wavenumber
k_F	Fermi wavenumber
k_B	Boltzmann's constant
L_m	mean-free path
L_ϕ	phase-coherence length
L_{sd}	spin-diffusion length
m	mass
m_e	electron rest mass
m_e^*	electron effective mass
m_h^*	hole effective mass
m^*	general effective mass
m_p	proton rest mass
μ_0	permeability of free space
μ	permeability (or chemical potential)
$\mu_{e(h)}$	electron (hole) mobility
Ψ, ψ	quantum mechanical state function
ω	radian frequency

$[\cdot, \cdot]$	commutator
$\langle \cdot \rangle$	expectation
$N(E)$	density of states
$\mathcal{O}$	observable
$\widehat{o}$	operator
$\mathbf{p}$, p	momentum
P	probability (or power)
q_e	electron charge
Q	charge
$\mathbf{r}$ (r)	position vector (or distance)
R	resistance
R_0	resistance quantum
R_t	tunnel resistance
t	time
T	temperature (or period or tunneling probability)
$\mathbf{v}$, v	velocity
v_F	Fermi velocity
$\mathbf{v}_g$, v_g	group velocity
$\mathbf{v}_p$, v_p	phase velocity
$\mathbf{v}_T$, v_T	thermal velocity
$\mathbf{v}_d$, v_d	drift velocity
V	potential energy (or voltage)
W	work
$e\phi$	work function
$e\chi$	electron affinity
ε_0	permittivity of free space
ε_r	relative permittivity
ε_n	Neumann's number
ρ	probability density function (or charge density)
λ	wavelength
λ_F	Fermi wavelength
λ_n	eigenvalue
σ	conductivity
$\tau_{\uparrow\downarrow}$	spin-flip time

List of acronyms used in text.

AFM	atomic force microscope
CMOS	complementary MOS
CN	carbon nanotube
CVD	chemical vapor deposition
DOS	density of states
DM	diamagnetic material
EUV	extreme ultraviolet
FET	field-effect transistor
FM	ferromagnetic material
HEMT	high electron mobility transistor
IC	integrated circuit
NIL	nanoimprint lithography
MOS	metal–oxide semiconductor
MOSFET	metal–oxide-semiconductor field-effect transistor
PM	paramagnetic material
QD	quantum dot
SEM	scanning electron microscope
SET	single-electron tunneling
SET	single-electron transistor
STM	scanning tunneling microscope
TEM	transmission electron microscope
TJ	tunnel junction

Appendix B

Physical Properties of Materials

I. Fundamental constants.

Quantity	Symbol	Value
Electron charge	q_e	-1.602×10^{-19} C
Proton charge	e	1.602×10^{-19} C
Speed of light in vacuum	c	2.998×10^{8} m/s
Planck's constant	h	6.626×10^{-34} J s
Planck's reduced constant	$\hbar\ (= h/2\pi)$	1.055×10^{-34} J s
Boltzmann's constant	k_B	1.381×10^{-23} J/K
Permittivity of free space	ε_0	8.854×10^{-12} F/m
Permeability of free space	μ_0	$4\pi \times 10^{-7}$ H/m
Electron rest mass	m_e	9.110×10^{-31} kg
Proton rest mass	m_p	1.673×10^{-27} kg

II. Fermi energy, free electron density, and conductivity for some elements.

Element	E_F (eV)	N_e^{3d} ($\times 10^{28}/m^3$)	σ ($\times 10^7/\Omega m$)
Cs (Cesium)	1.58	0.91	0.50
Rb (Rubidium)	1.85	1.15	0.80
K (Potassium)	2.12	1.40	1.39
Na (Sodium)	3.23	2.65	2.11
Ba (Barium)	3.65	3.20	0.26
Sr (Strontium)	3.95	3.56	0.47
Ca (Calcium)	4.68	4.60	2.78
Li (Lithium)	4.72	4.70	1.07
Ag (Silver)	5.48	5.85	6.21
Au (Gold)	5.51	5.90	4.55
Cu (Copper)	7.00	8.45	5.88
Mg (Magnesium)	7.13	8.60	2.33
Cd (Cadmium)	7.46	9.28	1.38
In (Indium)	8.60	11.49	1.14
Zn (Zinc)	9.39	13.10	1.69
Pb (Lead)	9.37	13.20	0.48
Ga (Gallium)	10.35	15.30	0.67
Al (Aluminum)	11.63	18.06	3.65
Be (Beryllium)	14.14	24.20	3.08

All values for room temperature except for Na, K, Rb, and Cs at 5 K and Li at 78 K.

III. Bandgap properties of several important semiconductors.*

Crystal	Gap type	E_g (eV) @ 0 K	E_g (eV) @ 300 K
Si	I	1.17	1.11
Ge	I	0.74	0.66
GaAs	D	1.52	1.43
InP	D	1.42	1.27
AlAs	I	2.23	2.16
CdS	D	2.58	2.42
CdSe	D	1.84	1.74
CdTe	D	1.61	1.44
ZnS	—	3.91	3.60

*For gap type, I indicates an indirect bandgap semiconductor, and D a direct gap semiconductor. (Table repeated from Section 5.4.4.) Data from Kittel, C. (1986). *Introduction to Solid State Physics*, 6th ed., New York: Wiley.

IV. Effective mass.

(m_e^* is the electron effective mass, and m_h^* is the hole effective mass.)

Semiconductor	Effective m_e^*/m_e	Mass m_h^*/m_e
Ge	0.12	0.04 0.28 0.08
Si	0.26	0.50 0.24
GaAs	0.067	0.50 0.08
GaP	0.35	0.50
CdSe	0.13	0.45
InP	0.073	0.40 0.08
InSb	0.015	0.39 0.02

V. Lattice constant for some compound (III-V and II-VI) semiconductors.

(The lattice constant (a) for Si is 0.543 nm, and for Ge, 0.566 nm.)

Material	a (nm)	Material	a (nm)	Material	a (nm)
ZnS	0.541	CdS	0.583	ZnTe	0.610
AlP	0.545	HgS	0.585	GaSb	0.610
GaP	0.545	InP	0.587	AlSb	0.614
GaAs	0.565	CdSe	0.605	HgTe	0.646
AlAs	0.566	InAs	0.606	CdTe	0.648
ZnSe	0.567	HgSe	0.608	InSb	0.648

VI. Properties of two semiconductor alloys.

$Ga_{1-x}Al_xAs$	$Cd_{1-x}Mn_xTe$
$E_g = (1.426 + 1.247x)$ eV	$E_g = (1.606 + 1.587x)$ eV
$m_e^* = (0.067 + 0.083x)\, m_e$	$m_e^* = (0.11 + 0.067x)\, m_e$
$m_{hh}^* = (0.62 + 0.14x)\, m_e$	$m_{hh}^* = \left(0.60 + 0.21x + 0.15x^2\right) m_e$
$\varepsilon_r = 13.18$	

VII. Static relative dielectric constant ε_r ($\varepsilon = \varepsilon_r \varepsilon_0$).

Material	ε_r
Si	11.7
Ge	15.8
GaAs	13.13
AlAs	10.1
AlSb	10.3
InP	12.37
InSb	17.88
CdSe	9.4
CdTe	7.2

VIII. Element symbols and names.

Symbol	Element	Symbol	Element	Symbol	Element
Ag	Silver	Ge	Germanium	Pd	Palladium
Al	Aluminum	H	Hydrogen	Pt	Platinum
Ar	Argon	He	Helium	Pu	Plutonium
As	Arsenic	Hg	Mercury	Ra	Radium
Au	Gold	I	Iodine	Rn	Radon
B	Boron	In	Indium	S	Sulfur
Ba	Barium	Ir	Iridium	Sb	Antimony
Be	Beryllium	K	Potassium	Sc	Scandium
Bi	Bismuth	Kr	Krypton	Se	Selenium
Br	Bromine	La	Lanthanum	Si	Silicon
C	Carbon	Li	Lithium	Sn	Tin
Ca	Calcium	Mg	Magnesium	Sr	Strontium
Cd	Cadmium	Mn	Manganese	Ti	Titanium
Ce	Cerium	Mo	Molybdenum	Tl	Thallium
Cl	Chlorine	N	Nitrogen	U	Uranium
Co	Cobalt	Na	Sodium	W	Tungsten
Cr	Chromium	Ne	Neon	Xe	Xenon
Cs	Cesium	Nb	Niobium	Y	Yttrium
Cu	Copper	Ni	Nickel	Zn	Zinc
F	Fluorine	O	Oxygen	Zr	Zirconium
Fe	Iron	P	Phosphorus		
Ga	Gallium	Pb	Lead		

Appendix

C

CONVENTIONAL MOSFETs

As described in the text, MOSFETs are the workhorses of the electronics industry, a fact that is unlikely to change soon. Therefore, in this appendix, the basic device operation of a conventional n-type enhancement mode MOSFET is briefly reviewed. Short-channel and hot-electron effects, device scaling, and other issues are ignored, and the emphasis is simply on gaining a physical understanding of device operation.

Consider the usual n-type MOSFET structure shown in Fig. C.1, where s, d, and g indicate the source, drain, and gate electrodes, respectively. There is also often a substrate contact at the bottom of the device (called the body contact), which is typically connected to the source. Here we consider a simplified structure without this contact. The circuit symbol of the n-channel FET is shown in Fig. C.2. The oxide layer is conventionally formed by oxidizing the silicon substrate, forming an SiO_2 insulating barrier between the gate electrode and the rest of the device, effectively blocking d.c. current. However, if the oxide is too thin (on the order of 1–2 nm), tunneling can occur. High dielectric constant insulators have been developed for MOS devices that can replace the SiO_2 layer, allowing for a thicker layer resulting in less tunneling.

As shown in Fig. C.1, there is no conduction channel between the source and the drain (both n-type Si) when the gate voltage V_{gs} is zero. (Throughout this appendix, we assume that the source is grounded.) Thus, $I_{ds} = 0$ irrespective of V_{ds}. When a positive gate voltage $V_{gs} > 0$ is applied, and has sufficient magnitude,† an inversion layer is formed under the gate, connecting the source and drain. (This is called an *enhancement type* MOSFET.) The inversion layer is formed since positive voltage V_{gs} pushes away holes, and attracts electrons under the gate, forming, in effect, an n-type channel, as shown in Fig. C.3. This

†In order to induce enough of a channel we need $V_{gs} > V_t$, where V_t is called the *threshold voltage*, which is typically on the order of a volt.

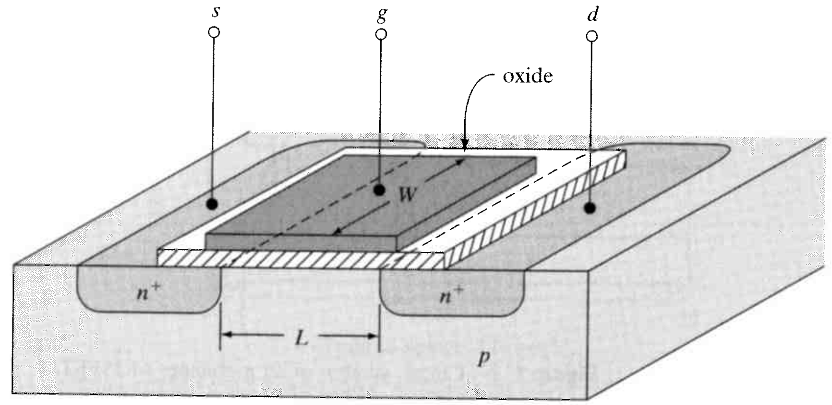

Figure C.1 Physical structure of an n-type MOSFET. The regions denoted as n^+ are heavily doped n-type Si, and p denotes the p-type Si substrate. For the gate electrode, typically poly crystalline silicon (*polysilicon*) is used for a variety of technical reasons, including leading to a lower threshold voltage.

allows current flow in the induced channel from drain to source upon applying a potential† $V_{ds} > 0$.

From an energy barrier viewpoint, there are barriers in two directions. A vertical energy barrier is between the gate and the substrate. (The barrier is basically the oxide.) A horizontal barrier is between the source and the drain. (The barrier is essentially the p-type substrate between the two n-type contacts.) Both the gate–oxide–substrate junction and the source-substrate-drain junction have energy profiles similar to the metal–insulator–metal junction depicted in Fig. 6.8 on page 193, although band bending actually occurs in the semiconducting regions. We will assume that the gate–oxide–substrate barrier is sufficiently high such that no current can flow from the gate into the device. However, the gate voltage plays a critical role. As V_{gs} is increased, forming an n-type channel as described earlier, the source–drain–substrate barrier is pushed down (Section 5.4.3), eventually below the filled states of the source and drain, and conduction can take place.

For an n-type MOSFET, device characteristics can be summarized as follows:

1. *Cut-off region*: When $V_{gs} < V_t$ the device is off. There is no conduction channel between the drain and the source, and, therefore,

$$I_{ds} = 0,$$

although weak current can arise due to what is called *subthreshold leakage* relating to minority carrier transport.

†The name "source" and "drain" is due to the fact that electrons flow from the source to the drain when $V_{ds} > 0$, current flow being defined in the opposite direction.

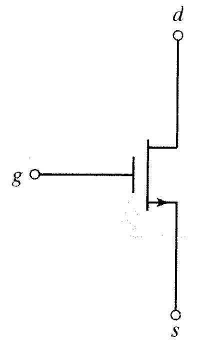

Figure C.2 Circuit symbol of an n-channel MOSFET.

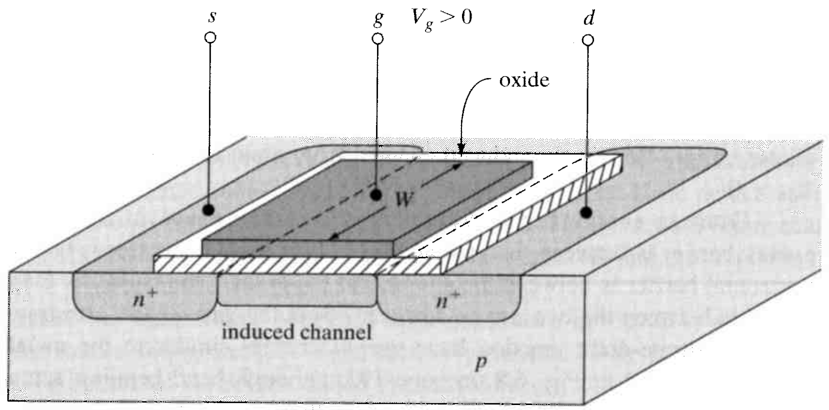

Figure C.3 MOSFET (n-type) with positive gate voltage, creating a conducting channel between source and drain.

2. *Triode or linear region*: When $V_{gs} > V_t$ and $V_{ds} < V_{gs} - V_t$ the device is on. (The inversion channel has been created.) In this region the MOSFET acts like a resistor controlled by the gate voltage. Drain to source current is

$$I_d = \frac{\mu_n C_{\text{ox}}}{2} \frac{W}{L} \left(2\left(V_{gs} - V_t\right) V_{ds} - V_{ds}^2\right). \qquad \text{(C.1)}$$

where μ_n is the electron mobility (Section 10.1), $C_{\text{ox}n}$ is the gate capacitance per unit area ($C_{\text{ox}} = \varepsilon_{\text{ox}}/t_{\text{ox}}$, where ε_{ox} is the oxide permittivity and t_{ox} is the oxide thickness), W is the gate width (i.e., the dimension into the paper), and L is the gate length (essentially, from the n^+ source to the n^+ drain).

Holding V_{gs} constant, as V_{ds} is increased the voltage along the channel increases from the source to drain. Therefore, the voltage from the gate to points along the channel decreases as one moves from the source to the drain. The channel depth (the "thickness" of the channel) is dependent on this voltage, and, thus, the channel near

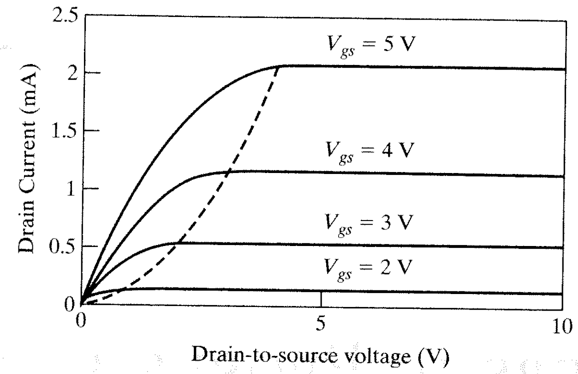

Figure C.4 Drain current versus drain-source voltage in an n-type MOSFET. The dashed line seperates the linear and saturation regions, and the different curves denote different positive gate voltages.

the drain becomes narrower than near the source. (The channel becomes tapered.) As V_{ds} is further increased, the voltage between the gate and the channel near the drain is reduced to V_t (when $V_{ds} = V_{gs} - V_t$), and the channel depth near the drain is reduced to almost zero. This point is called *pinch-off*, and beyond pinch-off, a further increase in the drain-source voltage will not significantly affect the drain current.† This is called the saturation region of operation.

3. *Saturation region*: When $V_{gs} > V_t$ and $V_{ds} > V_{gs} - V_t$ the device is on (the inversion channel has been created), but the channel is pinched off. The drain to source current is

$$I_d = \frac{\mu_n C_{\text{ox}}}{2} \frac{W}{L} \left(V_{gs} - V_t\right)^2. \qquad \text{(C.2)}$$

Fig. C.4 shows the I-V characteristics of a typical device.

†Even if the channel is pinched off well before the drain, so that it would seem like there is no longer a channel for current flow, current can still flow to the drain due to the high value of the electric field at that end of the device. That is, the relatively large drain voltage causes a large electric field between the pinched-off end of the channel and the drain. Electrons are transported across this depletion region by the strong electric field. Current is relatively insensitive to further changes in the drain voltage since this affects primarily the width of the depletion region.

Appendix D

Answers to Problems

Chapter 2: Classical Particles, Classical Waves, and Quantum Particles

1. For the photon, $E = 1.91$ eV. For the electron, $E = 3.56 \times 10^{-6}$ eV.
2. Yes, these wavelengths are the same.
3. $E_{\text{elec}} = 2.48 \times 10^{-13}$ eV, $E_{\text{oven}} = 9.92 \times 10^{-6}$ eV, $E_{\text{uv}} = 124.2$ eV.
4. (a) Each photon carries $E_p = 1.963$ eV.
   (b) $N = 3.18 \times 10^{15}$ photons/s.
5. $N = 3.18 \times 10^{16}$ photons/s. The number of photons scales linearly with power.
6. (a) $\lambda = 9.065 \times 10^{-13}$ m.
   (b) $\lambda = 8.631 \times 10^{-13}$ m.
   (c) $\lambda = 7.274 \times 10^{-8}$ m.
   (d) $\lambda = 4.969 \times 10^{-38}$ m.
7. $\lambda = 1.098 \times 10^{-34}$ m.
8. $m = 1.647 \times 10^{-35}$ kg.
9. $p = 1.035 \times 10^{-27}$ Js/m=kg m/s.
10. For the photon,

$$\lambda = 310.17 \text{ nm},$$
$$f = 9.672 \text{ Hz},$$
$$p = 2.136 \times 10^{-27} \text{ kg m/s}.$$

For the electron,

$$\lambda = 0.613 \text{ nm},$$
$$f = 9.672 \text{ Hz},$$
$$p = 1.080 \times 10^{-24} \text{ kg m/s}$$

For the proton,

$$\lambda = 0.0143 \text{ nm},$$
$$f = 9.672 \text{ Hz},$$
$$p = 4.630 \times 10^{-23} \text{ kg m/s}$$

11. $\lambda = 1.001$ nm.
12. (a) $\Delta v \geq 2.637 \times 10^{-30}$ m/s.
    (b) $\Delta v \geq 2.637 \times 10^{-34}$ m/s.
    (c) $\Delta v \geq 2.637 \times 10^{-36}$ m/s.
13. For the electron, $\Delta x \geq 5.789 \times 10^{-3}$ m. For the baseball, $\Delta x \geq 3.52 \times 10^{-32}$ m.
14. $\Delta v \geq 0.0115$ m/s.
15. $\Delta v \geq 5788.5$ m/s.

Chapter 3: Quantum Mechanics of Electrons

4. $u = \sqrt{2/a}\,\sin(n\pi x/a)$, $\lambda = (n\pi/a)^2$.
5. $u = \sqrt{\varepsilon_n/a}\,\cos(n\pi x/a)$, $\lambda = (n\pi/a)^2$, where

$$\varepsilon_n \equiv \begin{cases} 1, & n = 0 \\ 2, & n \neq 0 \end{cases}.$$

7. $\Delta E \geq 3.291 \times 10^{-8}$ eV.
8. 2. $\langle p_x \rangle = 0$.
9. $a_m = \int \psi_m^* (\mathbf{r})\, \Psi(\mathbf{r}, 0)\, dr^3$.
11. 0, $x = \pm L/4$.
12. 100 percent, 0 percent.
13. 1. $|a|^2 + |b|^2 = 1$.
    2. $P(E_2) = |b|^2$.
14. $\mathbf{J} = (\hbar k/m)\left(1 - |R|^2\right)$ on the left, and $\mathbf{J} = (\hbar q/m)\,|T|^2$ on the right.
15. $\mathbf{J} = 0$.
16. $k = 7.244 \times 10^9$ m^{-1}, $\omega = 3.039 \times 10^{15}$, $\mathbf{J} = \hat{\mathbf{z}}\, 3.355 \times 10^{10}$ A/m^2.

Chapter 4: Free and Confined Electrons

1. $\psi(z, t) = A e^{i(8.872 \times 10^9)z} e^{-i\left(\frac{3|q_e|}{\hbar}\right)t}$.
2. $\psi(z, t) = A e^{i(8.638 \times 10^8)z} e^{-i\left(\frac{3|q_e|}{\hbar}\right)t}$, $V = 2.971$ eV.
4. $n = 3.65 \times 10^{10}$, $E_{2,1,1} - E_{1,1,1} = 1.8 \times 10^{-39}$ J $= 1.124 \times 10^{-20}$ eV.

5. $n = 3.65$, $E_{2,1,1} - E_{1,1,1} = 1.8 \times 10^{-19}$ J $= 1.12$ eV.
6. For an electron, the space should be on the order of 0.776 nm, or smaller. For a proton, the space should be on the order of 0.0181 nm.
7. (a) $v = 1.3 \times 10^{-36}$ m/s.
   (b) $n = 1.3 \times 10^{34}$.
8. $P = 1/2$.
9. $v_e = 3.161 \times 10^5$ m/s.
10.
$$E_3 - E_1 = 0.752 \text{ eV},$$
$$E_3 - E_2 = 0.470 \text{ eV},$$
$$E_2 - E_1 = 0.282 \text{ eV},$$

11. (a) $A = \sqrt{30/L^5}$.
    (b) $c_n = 4\sqrt{15}\,(1 - \cos n\pi) / \left(n^3\pi^3\right)$.
    (c)
$$P(E_n) = |c_n|^2.$$
$$P(E_1) = 0.99856 = 99.8 \text{ percent.}$$
$$P(E_3) = 0.00137 = 0.137 \text{ percent.}$$
$$P(E_5) = 6.391 \times 10^{-5} = 0.0064 \text{ percent.}$$

12. 1. $A = \sqrt{630/L^9}$.
2. $$c_n = \begin{cases} 0, & n = 0, 2, 4, \ldots \\ \sqrt{\frac{1{,}260}{L^{10}}}\left(\frac{1}{\pi^5 n^5}\left(48L^5 - 4\pi^2 L^5 n^2\right)\right), & n = 1, 3, 5, \ldots. \end{cases}$$
3. $$P(E_n) = |c_n|^2.$$
$$P(E_1) = 0.9770 = 97.7 \text{ percent.}$$
$$P(E_3) = 0.0215 = 2.15 \text{ percent.}$$
$$P(E_5) = 0.00122 = 0.122 \text{ percent.}$$

13. $31.963/L^2$ eV, where L is in nm.
14. $\mu = 0.135$ eV.
17. For the infinite-height well, $E_1 = 0.0235$ eV, $E_3 = 0.21152$ eV. For the finite-height well, as a representative result, at $V_0 = 0.5$ eV, for E_1 we have $E_{\text{numerical}}^{\text{finite-height}} = 0.01812$ eV, and for E_3 we have $E_{\text{numerical}}^{\text{finite-height}} = 0.16085$ eV.
18. $\langle E \rangle = E_1$.
19. $\langle r \rangle = 6a_0$.
20. $\langle r \rangle = 5a_0$.
21. $\left(v_g\right)_z = 2.953 \times 10^5$ m/s.
22. $L \leq \lambda_e = 0.708$ nm.

Chapter 5: Electrons Subject to a Periodic Potential—Band Theory of Solids

1. We need a material cube having side length 2.5 nm.
2. The bandedges are at $E = 0.217$ eV and $E = 0.459$ eV.
4. $\mathbf{J}(\mathbf{r}, t) = \widehat{\mathbf{x}}\frac{p}{m}u^2$.
5. $m^* = (3/2)\,m$.
6. $m^* = -2m/\cos k$, $v_g = -\hbar \sin k/2m$.
7. $x(t) = \frac{2A}{\mathcal{E}q_e}\left(\cos\left(q_e\mathcal{E}at/\hbar\right) - 1\right)$.
8. $m^* = 5m_e/2$.
10. 5.32 eV.
11. 0.347 eV.
12. $\lambda = 174.67$ nm.
13. Metal.
14. Insulator, Semiconductor.
17. $\lambda = 721.3$ nm.
18. $E_{pn} = 0.20$ eV, $k_{pn} = k_a$.
19. (a) $\Delta E = 10.2$ eV, $\lambda = 121.6$ nm, between visible and UV.
    (b) $\Delta E = 0.306$ eV, $\lambda = 4054.5$ nm, far infrared.
    (c) $\Delta E = 0.0319$ eV, $\lambda = 3.89 \times 10^{-5}$ m, microwave.
    (d) $\Delta E = 3.188$ eV, $\lambda = 389.2$ nm, visible, violet.
    (e) $\Delta E = 13.51$ eV, $\lambda = 91.83$ nm, between visible and UV.
    (f) $\Delta E = 13.6$ eV, $\lambda = 91.23$ nm, between visible and UV.
20. (a) $E = 1.426$ eV, (b) —, (c) magnitude of applied field greater than 5.5×10^5 V/m.
22. $r_{(19,0)} = 0.7437$ nm, $r_{(10,10)} = 0.678$ nm. For $(n, 0)$, $n = 9$.

Chapter 6: Tunnel Junctions and Applications of Tunneling

3. $V_0 = 6.858$ eV.
4. (a) $2e^{-9.48\times10^{35}}$.
6.
$$T = \left|\frac{2k_1}{k_1 + k_2}\right|^2, \tag{D.1}$$
$$R = \left|\frac{k_1 - k_2}{k_1 + k_2}\right|.$$

9. $T = 0.791$. For $a = 2$ nm, $T = 0.515$, for $a = 5$ nm, $T = 0.293$, and for $a = 10$ nm, $T = 0.901$.
10. $T \simeq e^{-2a\sqrt{\frac{2m^*}{\hbar^2}(V_0 - E)}}$.

Chapter 7: Coulomb Blockade and the Single-Electron Transistor

1. $\tau = 5.0 \times 10^{-14}$.

2. $T \ll 1,855$ K. For $C = 1.2$ pF, $T \ll 7.73 \times 10^{-4}$ K.

4. $V > -Nq_e/2C$.

6. $T = |q_e|/I_s$.

8. $V_s > 13.42$ V.

11. $V_s > 1.41$ V.

14. (a) $\lambda = 0.548$ nm.
(b) $L \leq \lambda$.

15. $|\mathbf{F}| = 4.617 \times 10^{-12}$ N, at 10 μm, $|\mathbf{F}| = 4.617 \times 10^{-18}$ N.

Chapter 8: Particle Statistics and Density of States

4. (a)

$$E_F = \left(\frac{hN_f}{3\sqrt{2m}}\right)^{3/2}.$$

(b) The Fermi wavelength is the de Broglie wavelength at the Fermi energy.

6. $\lambda_F^{(2d)} = 0.571$ nm.

7.

$$\lambda_F = 0.359 \text{ for aluminum} \tag{D.2}$$

$$= 0.399 \text{ nm for zinc.} \tag{D.3}$$

8. $n \simeq N_d = 10^{14}$ cm^{-3}.

Chapter 9: Models of Semiconductor Quantum Wells, Quantum Wires, and Quantum Dots

2. For GaAs, $L < 36$ nm, and for Si, $L < 18$ nm.

4. $L_x \ll 3.86$ nm.

6. $\alpha = 0.25$.

8. For the infinite-height well, $E_1 = 0.056$ eV, $E_3 = 0.505$ eV. For the finite-height well, $E_1 = 0.036$ eV and $E_3 = 0.275$ eV .

9. The first two states will be filled.

11. $E_{n_x,n_y,n_z} = 0.334\left(n_x^2 + n_y^2 + n_z^2\right)$ eV.

12. $R = 0.613$ nm.

13. $E_{1,1,1} - E_{2,2,1} = -0.251$ eV.

14. $E_g^{2\text{ nm dot}} = 2.735$ eV, $\lambda = 453.67$ nm (blue-violet).

$$E_g^{3\text{ nm dot}} = 2.497 \text{ eV}, \ \lambda = \frac{hc}{2.497\,|q_e|\,10^{-9}} = 496.81 \text{ nm (orange-yellow).}$$

Chapter 10: Nanowires, Ballistic Transport, and Spin Transport

1. $v_T = 6.66 \times 10^4$ m/s, $v_F = 3.635 \times 10^5$ m/s.

2. $|\mathbf{v}_d| = 3.517$ m/s, $\sigma = 1.916 \times 10^8$ S/m.

3.

$$\sigma = \frac{q_e^2 \tau N_e}{m_e(i\omega\tau + 1)}.$$

4. $L_{\text{mfp}} = 135.3$ nm.

6. $d \geq 0.046$ nm for copper, $d \geq 8.235$ nm for silicon.

9. $v = 1.897 \times 10^8$ m/s.

11.

$$R = \frac{1}{\sigma 4\pi}\left(\frac{1}{a} - \frac{1}{b}\right).$$

13. $I = 92.98$ μA.

14. $I = 46.5 \times 10^{-6}$ A.

15. $I = 30.99 \times 10^{-6}$ A.