Technologies to watch in 2004 according to CNN
(after David Pescovitz Posted at CNN WEB site 12/14/03)

1. **Ultra-wideband**
2. **RFID**
3. **Home networking**
4. **Wireless broadband (WiMax)**
5. **Micro fuel cells**
6. **Gecko tape (instead of VELCRO)**
7. **OLEDs**
8. **LED lightbulbs** (80 percent less energy)
9. **MRAM:** Magnetoresistive random access memory is faster than the fastest current nonvolatile flash memory and DRAM.
10. **Bioinformatics**

Technologies to watch in 2009 according to http://www.electronicsweekly.com

- 1. Picocells
- 2. Bluetooth/WiFi
- 3. Medical implants/low power RF
- 4. Energy harvesting
- 5. Smart metering

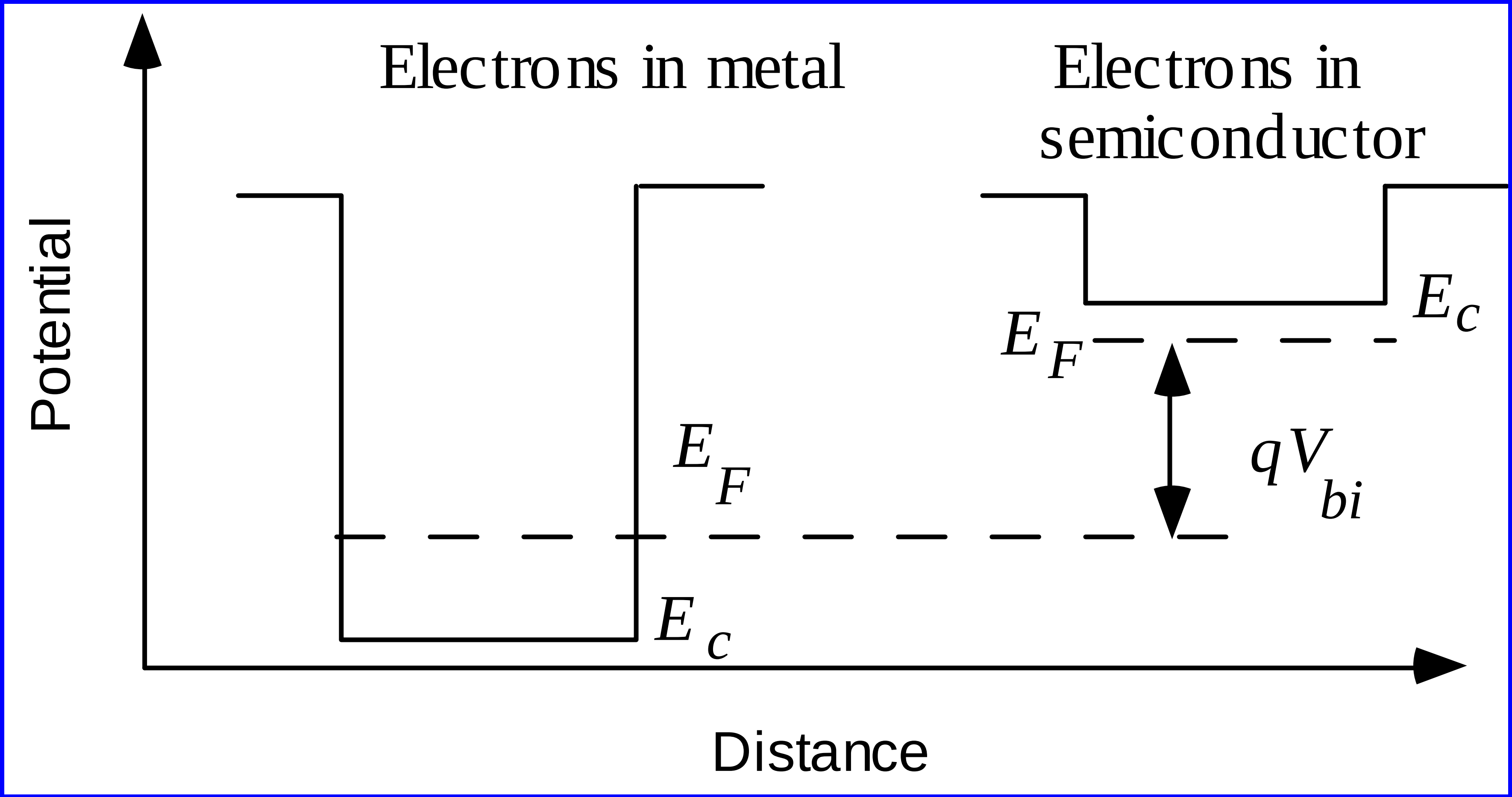
Device Building Blocks

- Metal-semiconductor contacts
  - Schottky contact
  - Ohmic contact
- p-n junction
- MOS structure
- Heterointerface
- Quantum well
- Superlattice
- Quantum wire
- Quantum dot
- Quantum electronic island

Walter Schottky

1886–1976

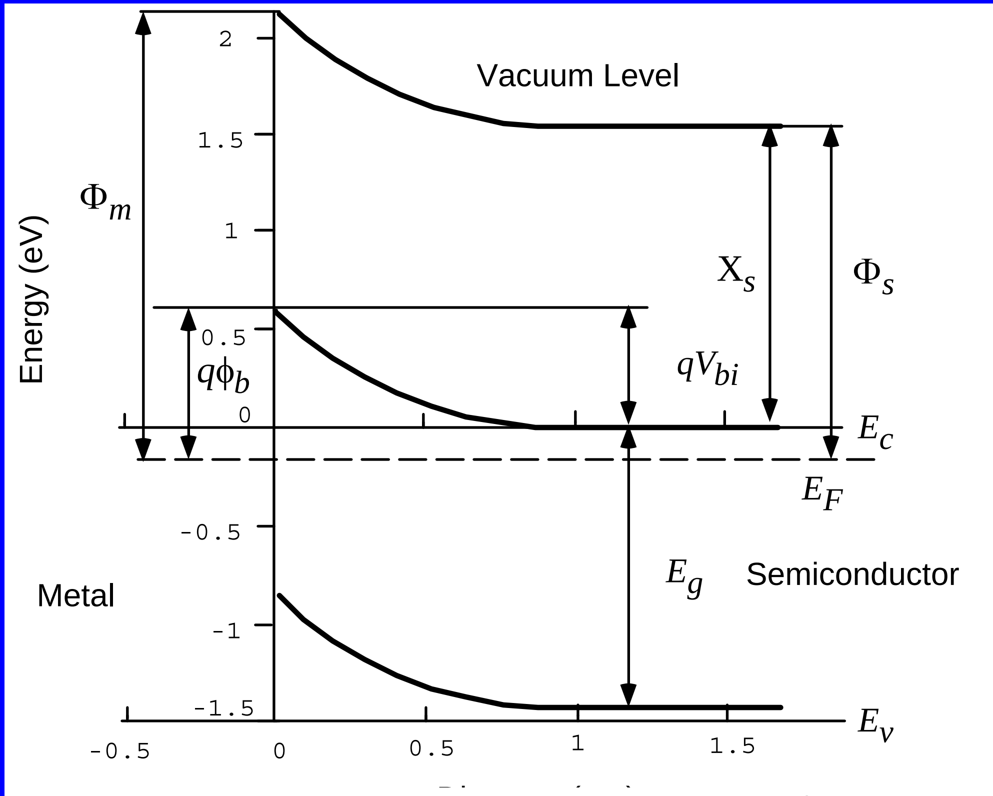
Schematic energy diagram



From M. Shur, Introduction to Electronic Devices, Wiley, 1996

Explanation

A semiconductor is doped n-type. Electrons transfer from the semiconductor layer near the surface into the metal, where they have a lower energy. They leave behind a positive charge of depleted donors. The attraction of the electrons by this positive charge compensates the attraction of a lower energy in the metal.



Schottky contact Energy Band Diagram

Energy diagram of GaAs metal-semiconductor barrier.

$q\phi_b$ is the barrier height (0.75 eV)

X_s is the electron affinity in the semiconductor

Φ_s and Φ_m are the semiconductor and the metal work functions

V_{bi} (0.591 V) is the built-in voltage.

Donor concentration in GaAs is 10^{15} cm^{-3}.

(From M. Shur, Introduction to Electronic Devices, Wiley, 1996

Quote from Sir Francis Bacon, Novum Organum, 1620

- Nature to be commanded, must be obeyed.

Depletion Region under Zero Bias

$$F = -\frac{qN_d(x_n - x)}{\varepsilon_s}$$

$$\phi = -\frac{qN_d(x_n - x)^2}{2\varepsilon_s} = -V_{bi}\left(1 - \frac{x}{x_n}\right)^2$$

$$x_n = \sqrt{\frac{2\varepsilon_s V_{bi}}{qN_d}}$$

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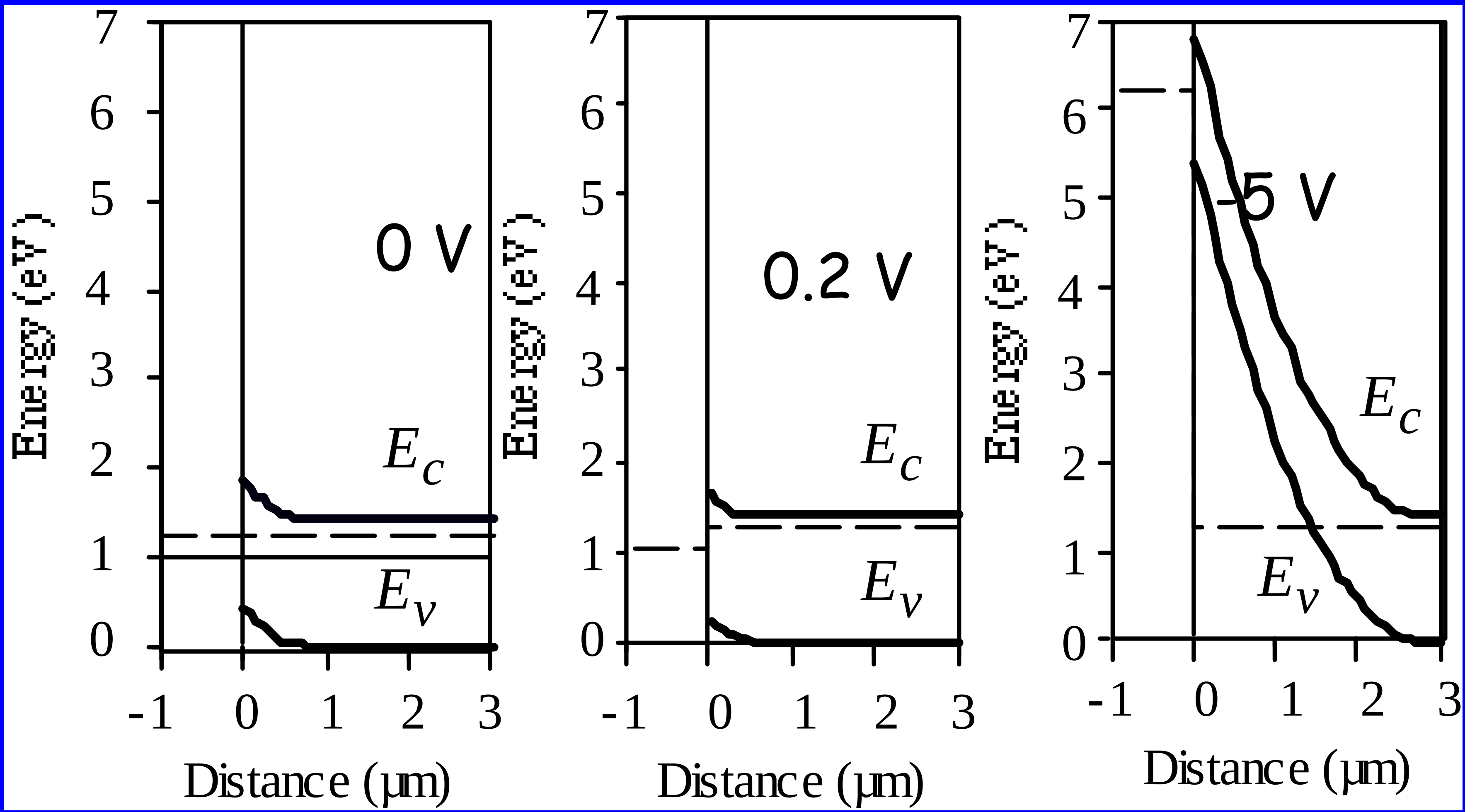
Effect of bias



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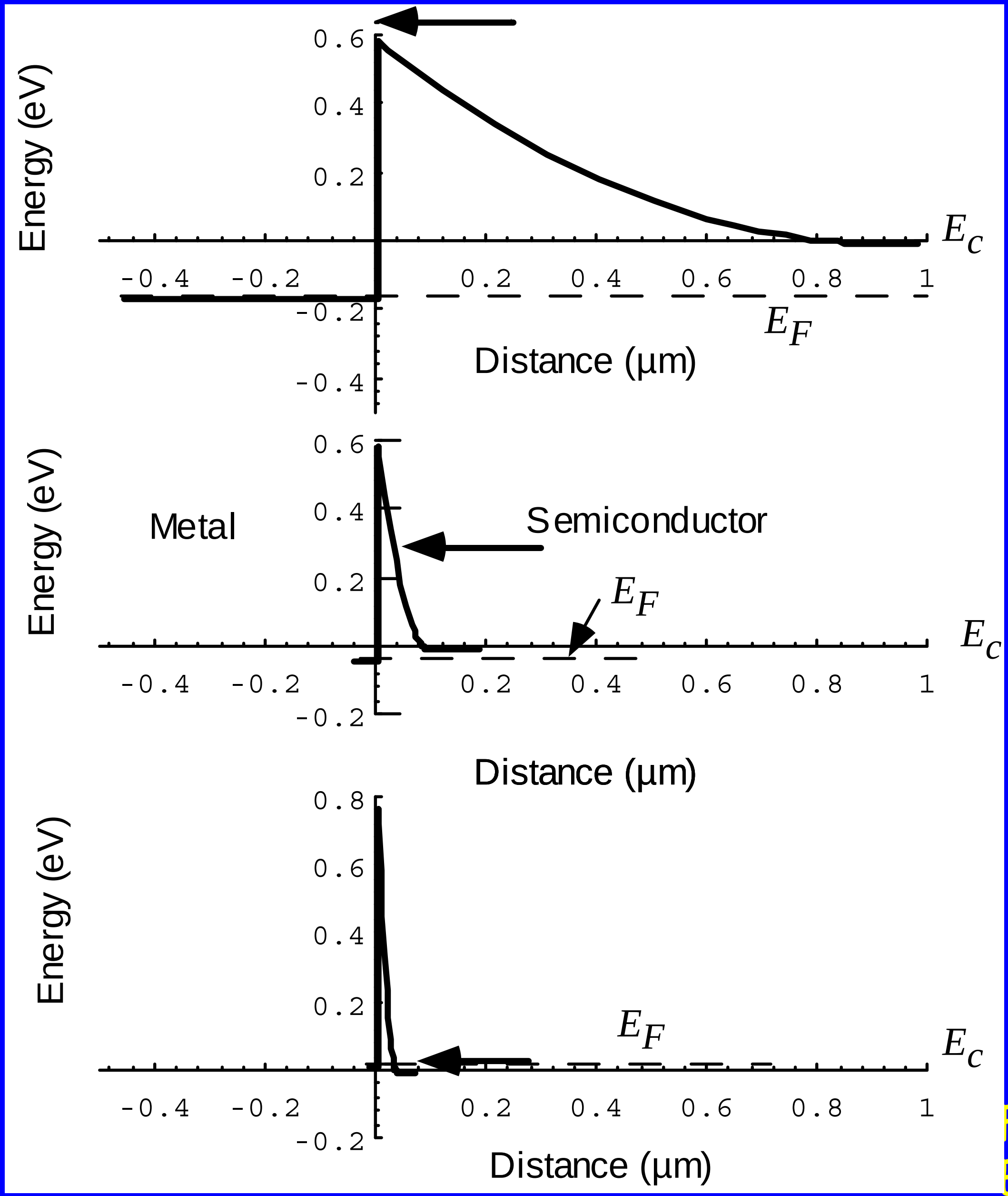
Effect of Doping



From M. Shur, Introduction to Electronic Devices, Wiley, 1996

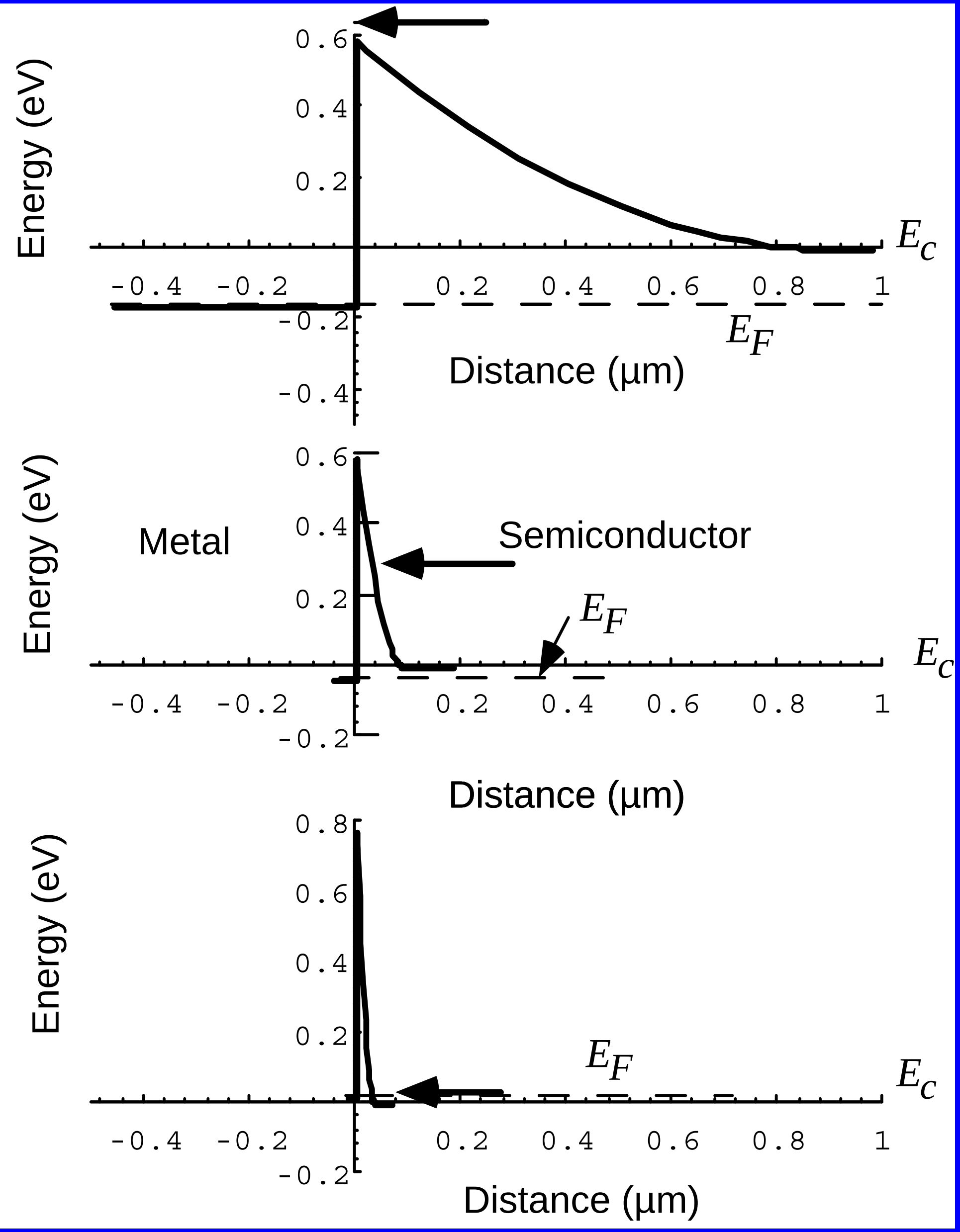
Diode equation for Schottky Diode

$$I = I_s \left[\exp\left(\frac{V - IR_s}{\eta V_{th}} \right) - 1 \right]$$

Thermionic, Thermionic Field, and Field Emission

Thermionic emission

$$j_{ss} = A^{*}T^{2}\exp\left(-\frac{\phi_b}{k_B T}\right)$$



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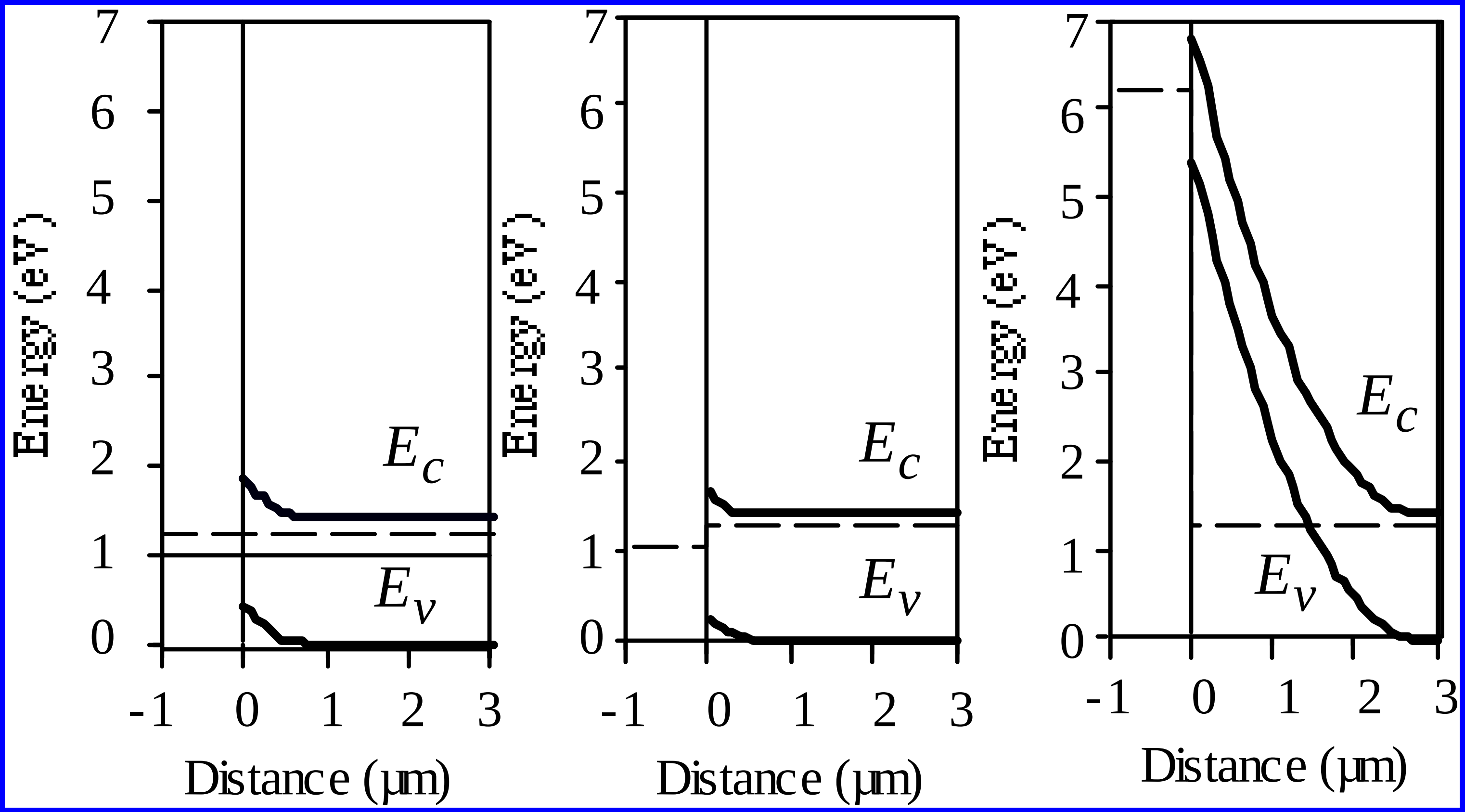
Example:

Estimate the doping density in the GaAs layer from the data in the figure. The dielectric permittivity ε = 1.14×10^{-10} F/m. The electronic charge q = 1.602×10^{-19} C.

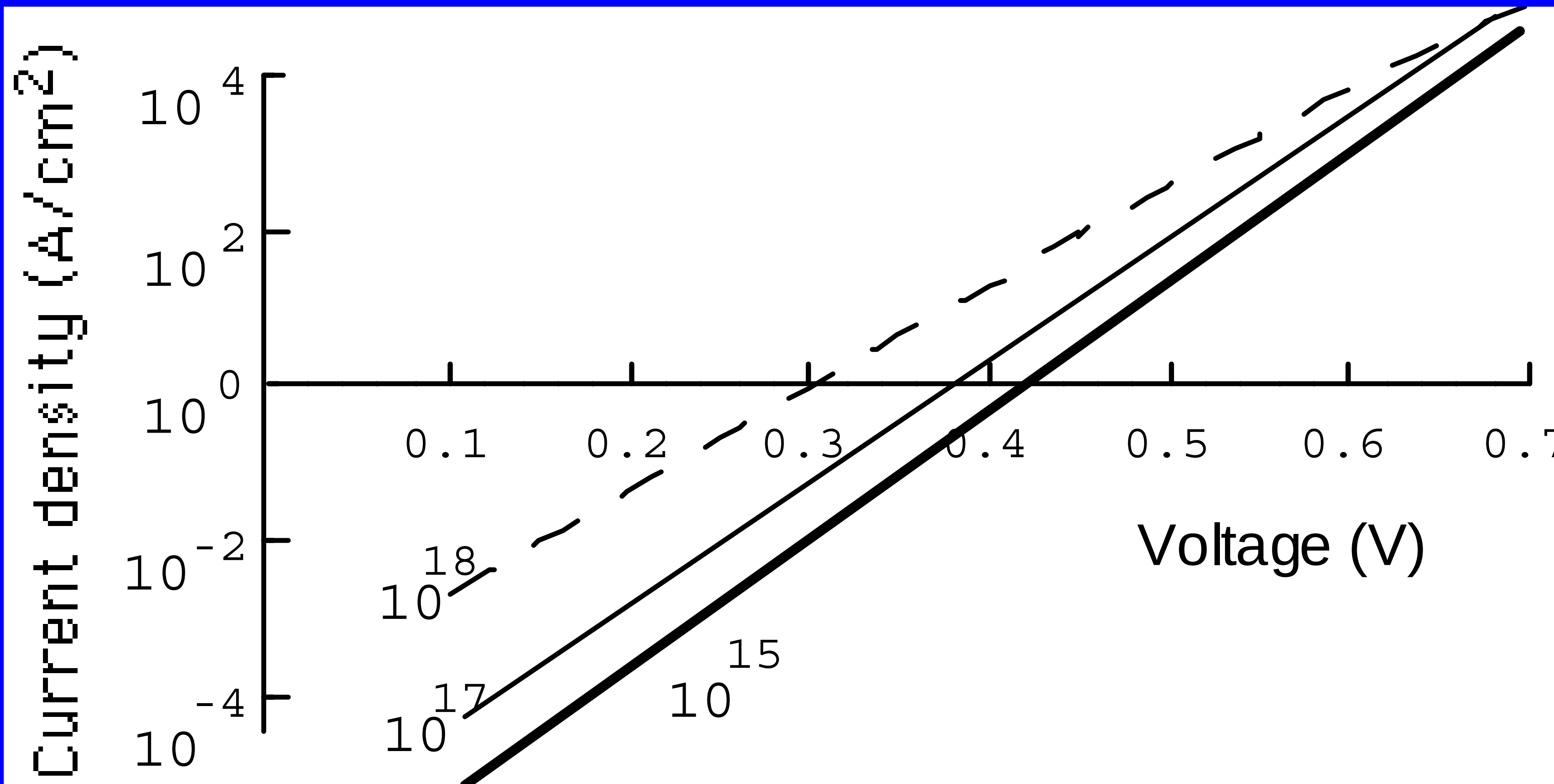


Solution

From the figure, the depletion width, x_n, at - 5 V bias is approximately 2.5 μm corresponding to the voltage drop of approximately V_{dep} = 5. 8 V. The doping density $N_d = 2\varepsilon V_{dep}/q\,d^2 = 1.3\text{x}10^{15}\ \text{cm}^{-3}$

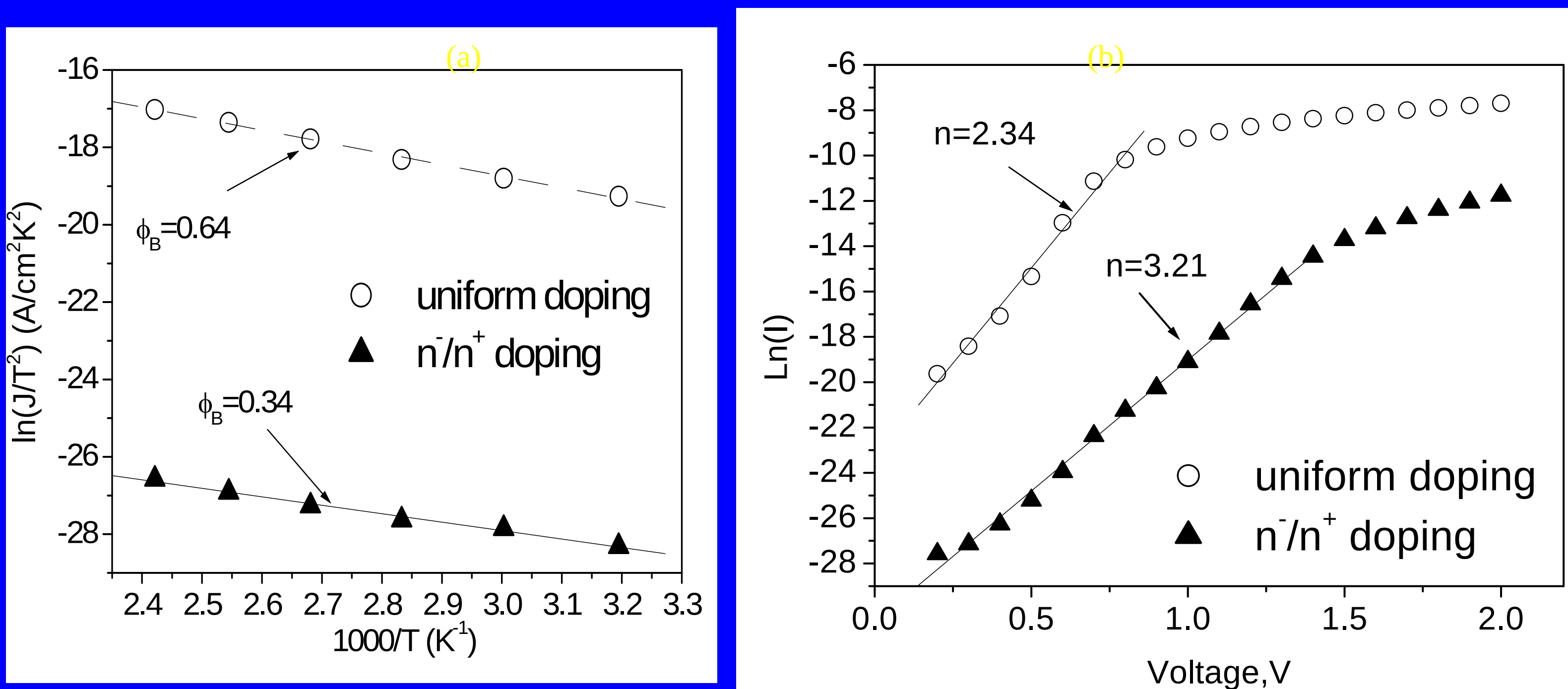
Forward current-voltage characteristics

Current density (A/cm²)



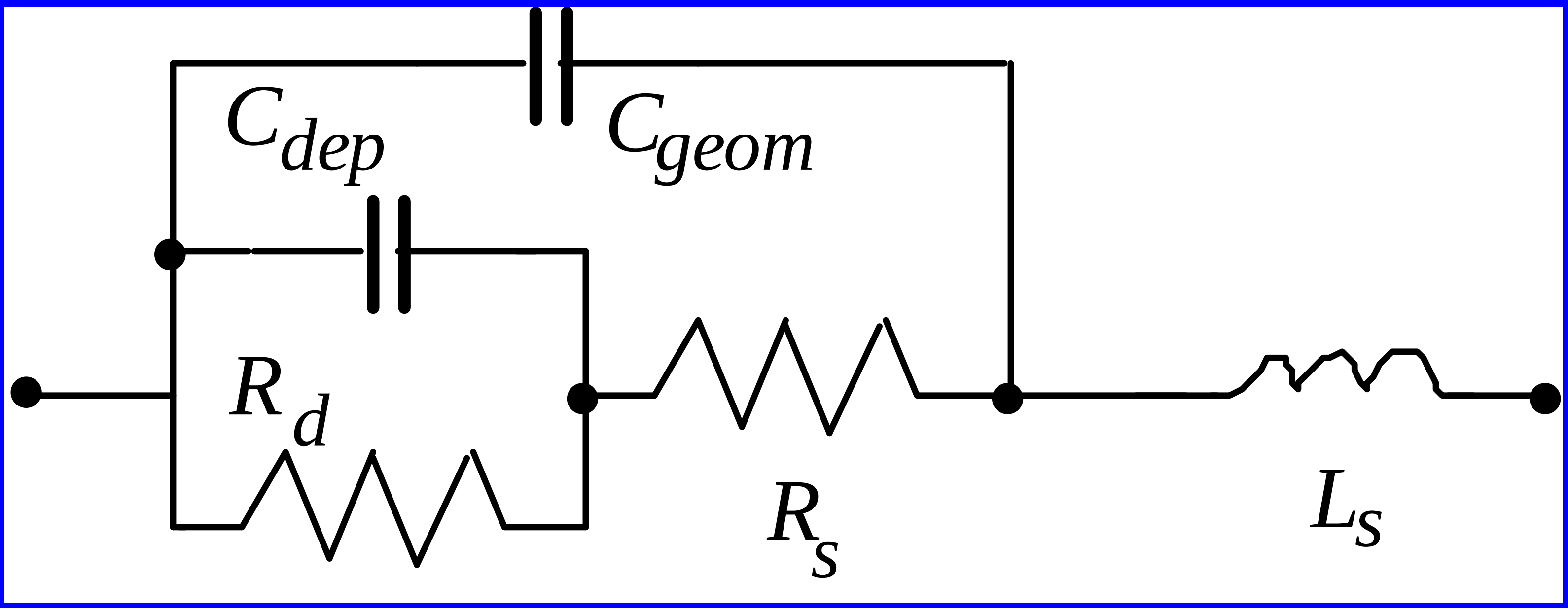
From M. Shur, Introduction to Electronic Devices, Wiley, 1996

Non-ideal Schottky diodes (to AlGaN)



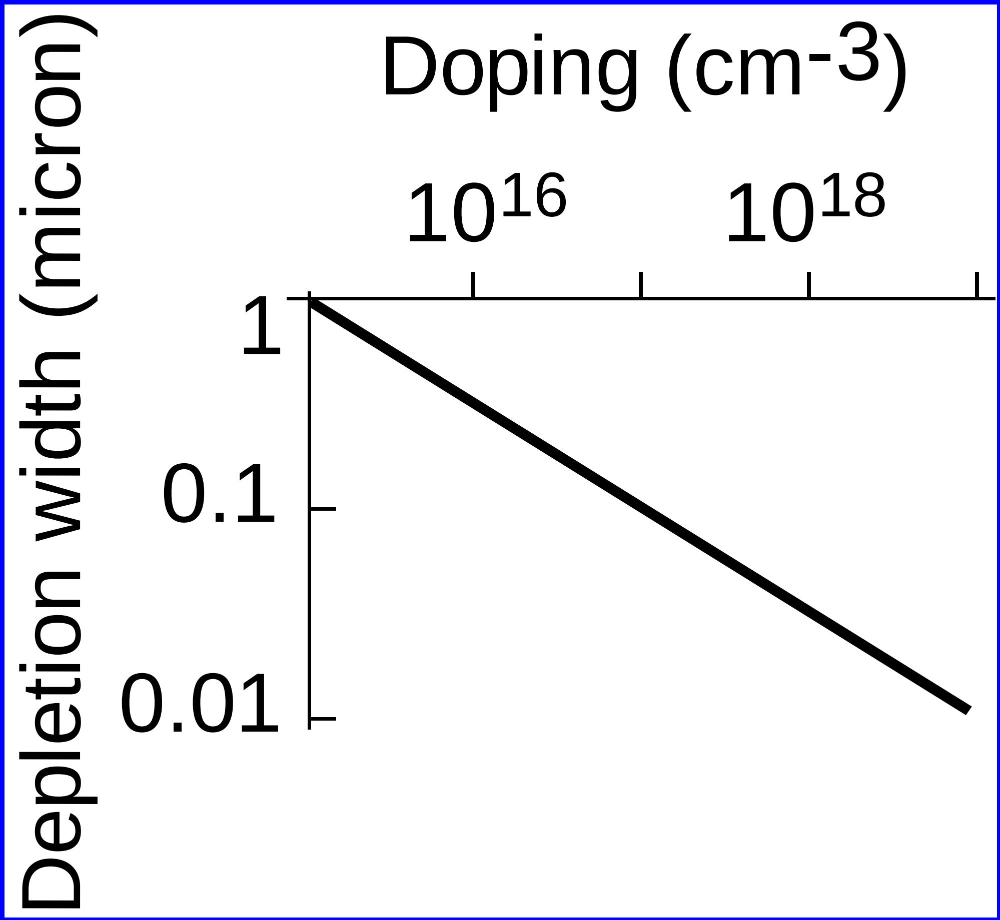
From V. Adivarahan, G. Simin, J. W Yang, A. Lunev and M. Asif Khan, N. Pala, M. Shur, and R. Gaska, SiO2 passivated lateral-geometry GaN transparent Schottky barrier detectors, Appl. Phys. Lett., Vol. 77, No 6, pp. 863-865, August (2000)

Equivalent Circuit

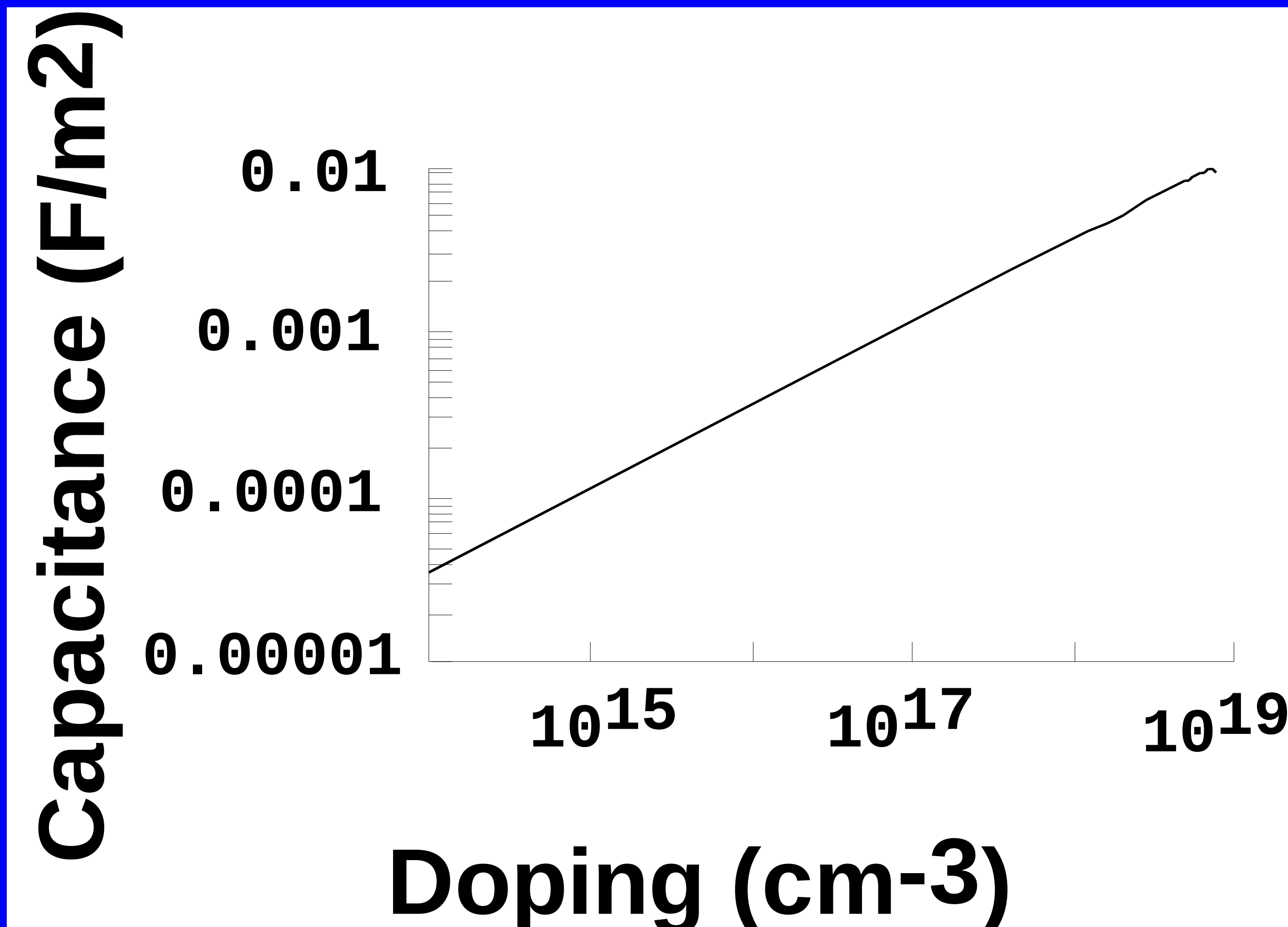


From M. Shur, Introduction to Electronic Devices, Wiley, 1996

Depletion width versus doping

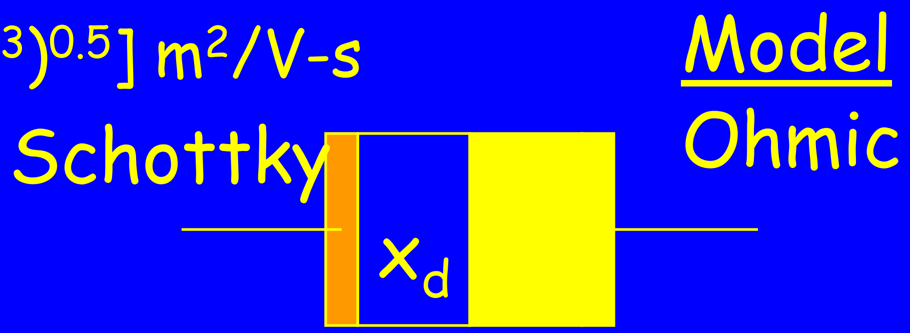


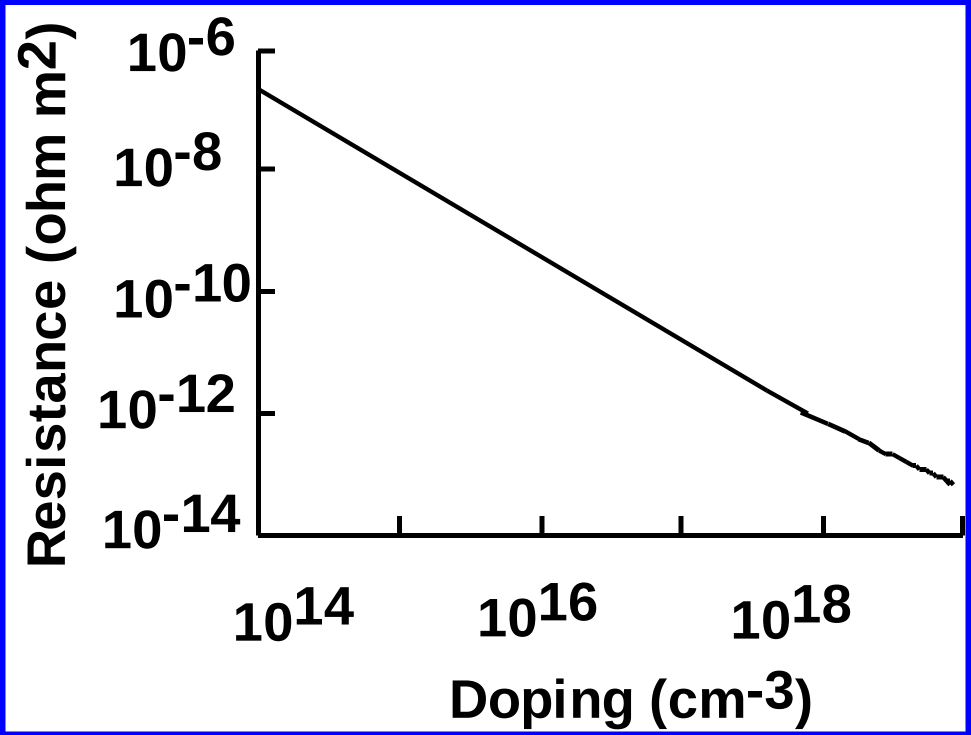
Depletion capacitance



Series resistance

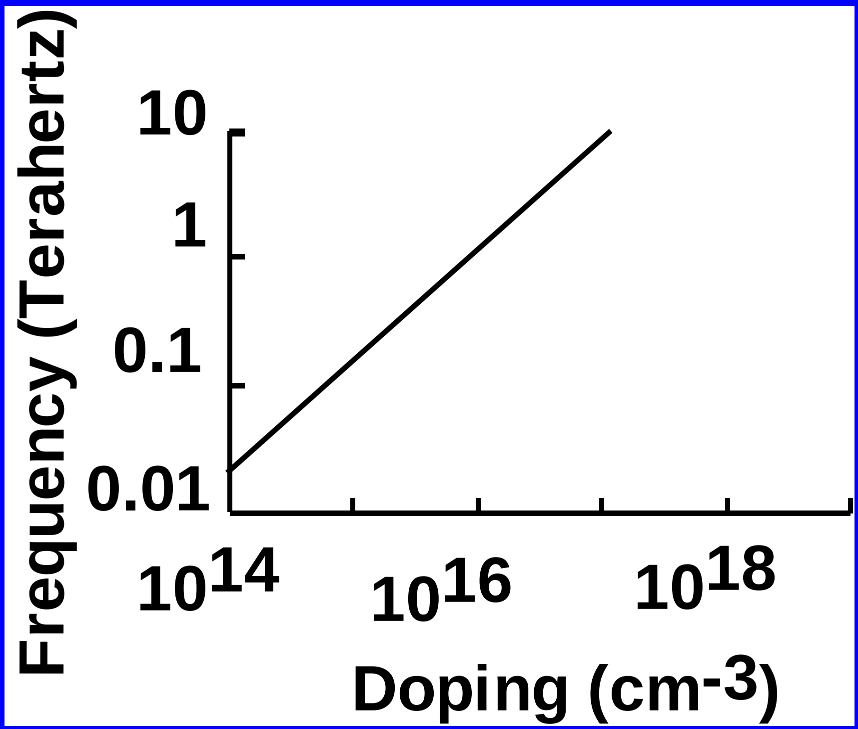
$\mu = 0.94/[1+(N_d/10^{23})^{0.5}]\ m^2/V\text{-}s$





Cutoff frequency (Upper limit)

$$f_t = 1/(2\pi C_d R_s) = q\ \mu\ Nd/(2\ \pi\ \varepsilon)$$



Proportional to inverse Maxwell dielectric relaxation time!

SPICE Simulation of Schottky Diodes

Spice Parameter	Spice Parameter Name	Unit	Schottky Diode Value	Our notation
TT	Transit time	s	0	t_{tr}
EG	Energy gap	eV	0.65	ϕ_b
XTI	Saturation current temperature exponent	-	2η	κ

$$I_s(T) = I_s(T_o)\left(\frac{T}{T_o}\right)^{\frac{\kappa}{\eta}} \exp\left(\frac{E_g}{k_B T_o}\right) \exp\left(-\frac{E_g}{k_B T}\right)$$

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Equations describing Schottky diodes

Space charge density in the depletion layer	$\rho = qN_d$
Field distribution in the depletion layer	$F = -\frac{qN_d(x_n - x)}{\varepsilon_s}$
Potential distribution in the depletion layer	$\phi = -\frac{qN_d(x_n - x)^2}{2\varepsilon_s} = -V_{bi}\left(1 - \frac{x}{x_n}\right)^2$
Depletion layer width	$x_n = \sqrt{\frac{2\varepsilon_s(V_{bi} - V)}{qN_d}}$
Empirical diode equation	$I = I_s\left[\exp\left(\frac{V}{\eta V_{th}}\right) - 1\right]$
Parallel leakage current	$I_{leakage} = G_{\min} V$
Diode equation (with series resistance)	$I = I_s\left[\exp\left(\frac{V - IR_s}{\eta V_{th}}\right) - 1\right]$
Reverse diode current density (saturation current density)	$J_{ss} = A^* T^2 \exp\left(-\frac{\phi_b}{V_{th}}\right)$ where $A^* = \alpha\frac{m_n q k_B^2}{2\pi^2\hbar^3} \approx 120\,\alpha\frac{m_n}{m_e}\left(\frac{\mathrm{A}}{\mathrm{cm}^2\mathrm{K}^2}\right)$
Temperature dependence of the saturation current	$I_s(T) = I_s(T_o)\left(\frac{T}{T_o}\right)^2 \exp\left(\frac{\Phi_b}{k_B T_o}\right)\exp\left(-\frac{\Phi_b}{k_B T}\right)$

From M. Shur, Introduction to Electronic Devices, Wiley, 1996

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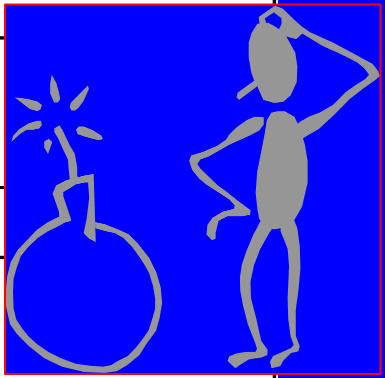
Summary. Schottky Diodes.

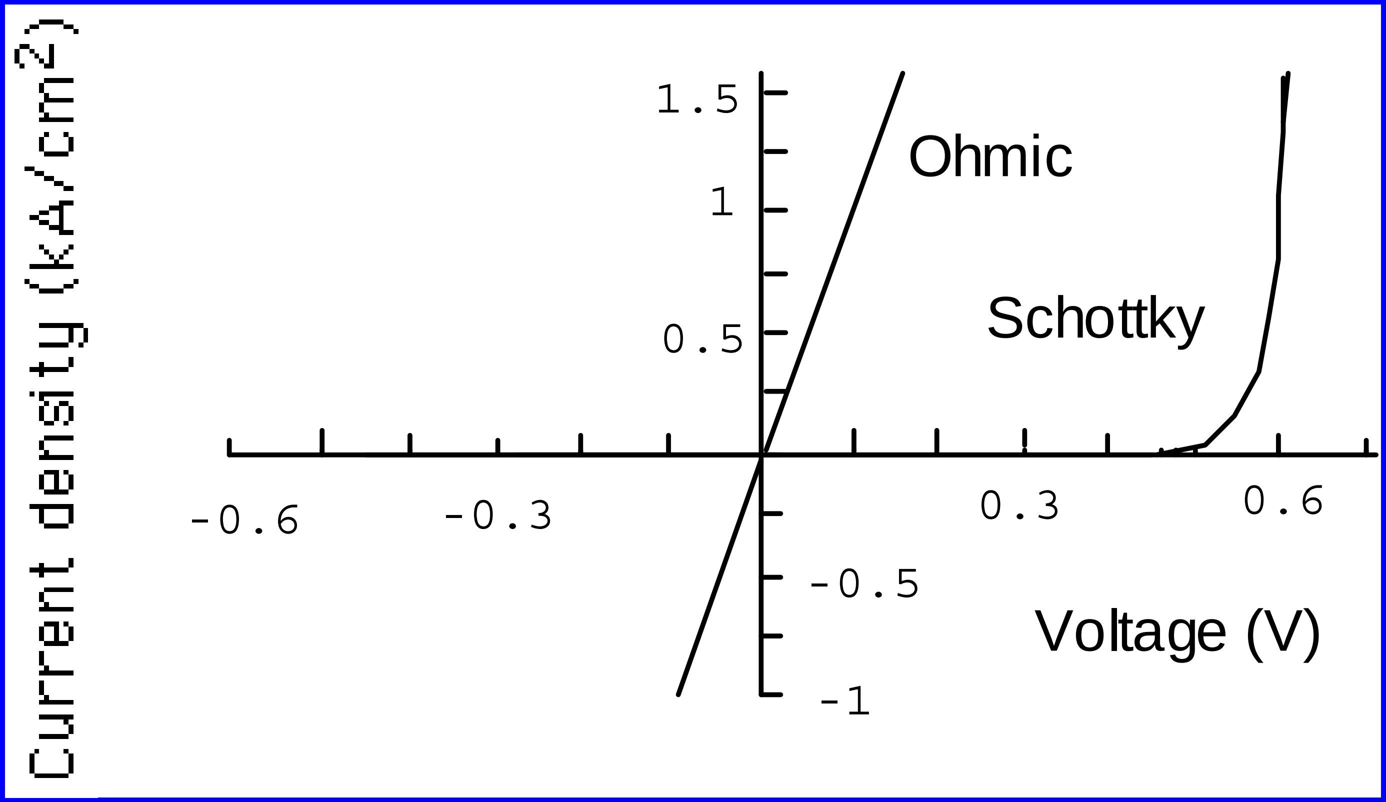
Space charge density in the depletion layer	$\rho = qN_d$
Field distribution in the depletion layer	$F = -\dfrac{qN_d(x_n - x)}{\varepsilon_s}$
Potential distribution in the depletion layer	$\phi = -\dfrac{qN_d(x_n - x)^2}{2\varepsilon_s} = -V_{bi}\left(1 - \dfrac{x}{x_n}\right)^2$
Depletion layer width	$x_n = \sqrt{\dfrac{2\varepsilon_s(V_{bi} - V)}{qN_d}}$
Empirical diode equation	$I = I_s\left[\exp\left(\dfrac{V}{\eta V_{th}}\right) - 1\right]$
Parallel leakage current	$I_{leakage} = G_{\min} V$
Diode equation (with series resistance)	$I = I_s\left[\exp\left(\dfrac{V - IR_s}{\eta V_{th}}\right) - 1\right]$



Crude rule of thumb $\Phi_b = 2E_g/3$

Ohmic Contacts

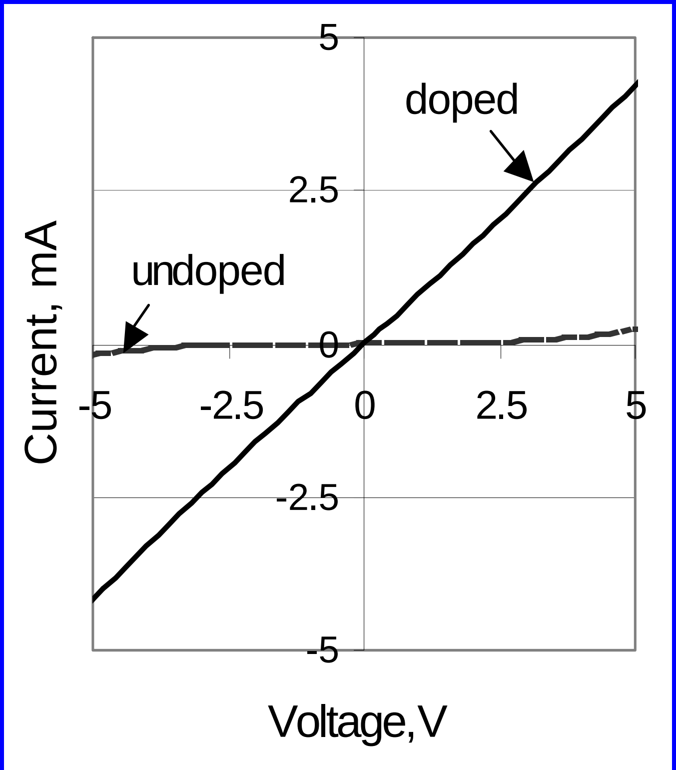
$R_c = 10^{-4}$ ohm cm^2

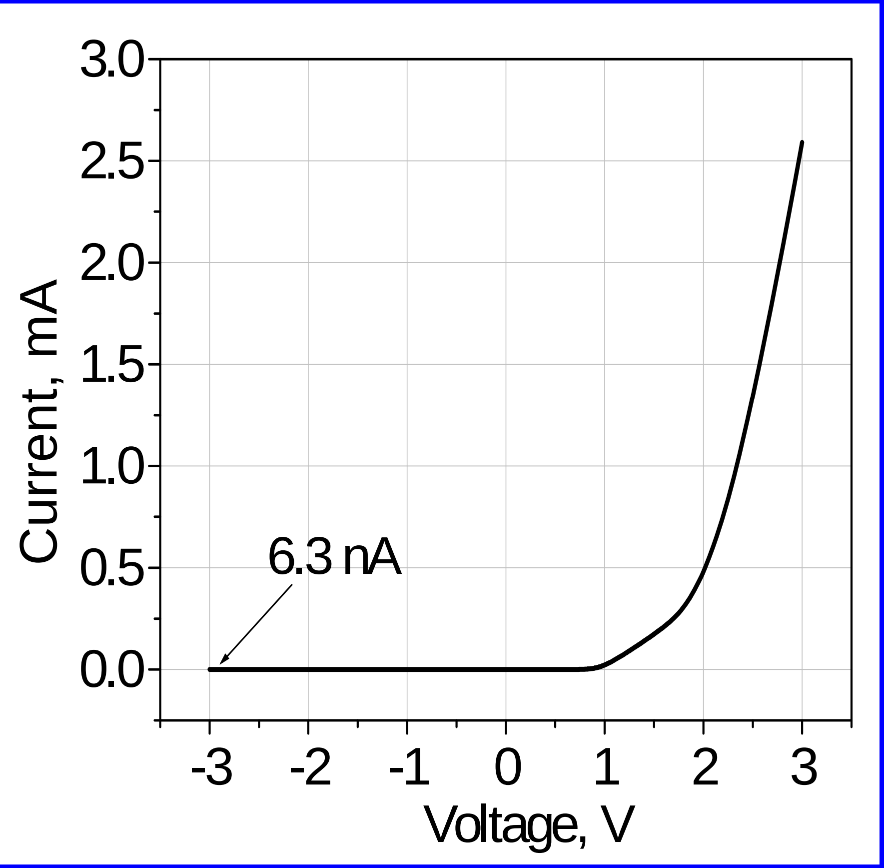


Best $R_c = 10^{-8}$ ohm cm^2

I-Vs of ohmic contacts to n-doped AlGaN (a) and of the AlGaN photodiode (b).

Dashed line in the left figure shows the I-V curve for undoped AlGaN layer.





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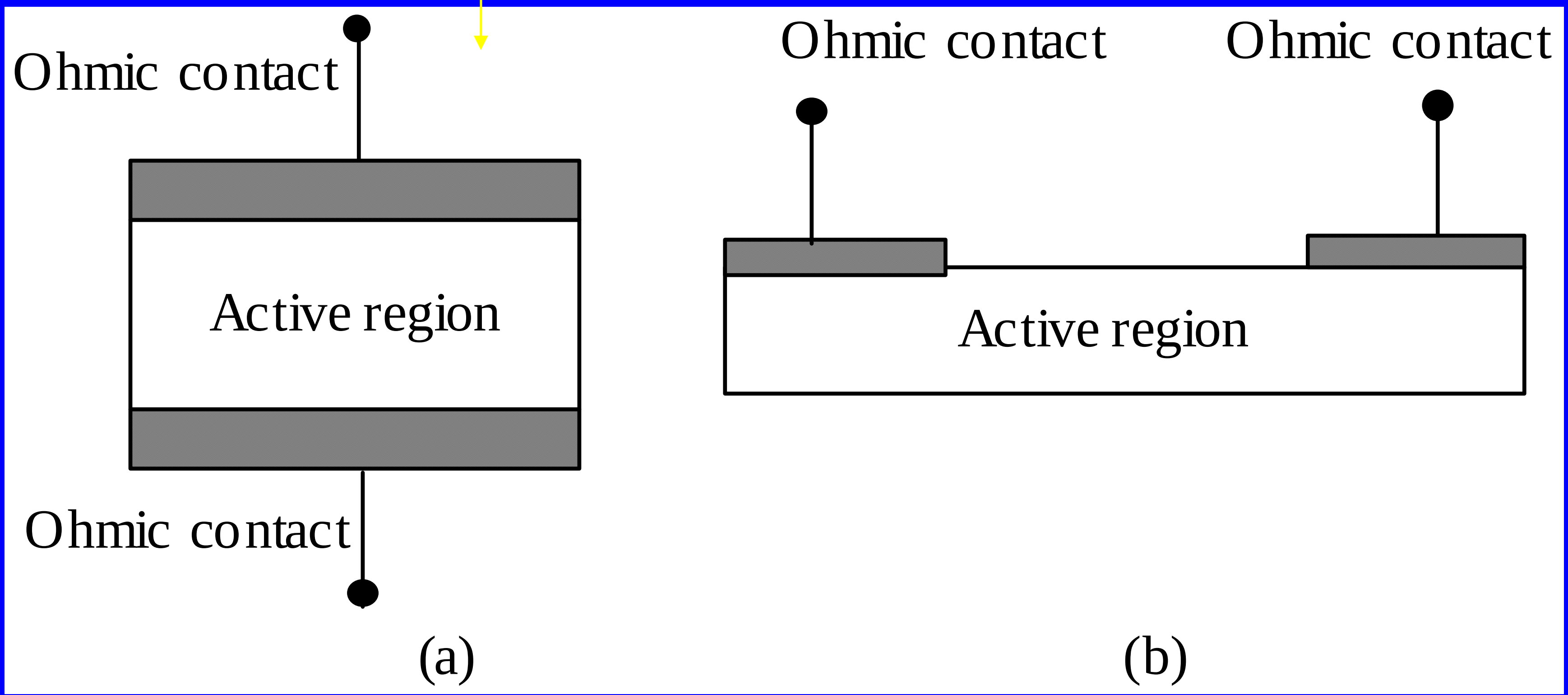
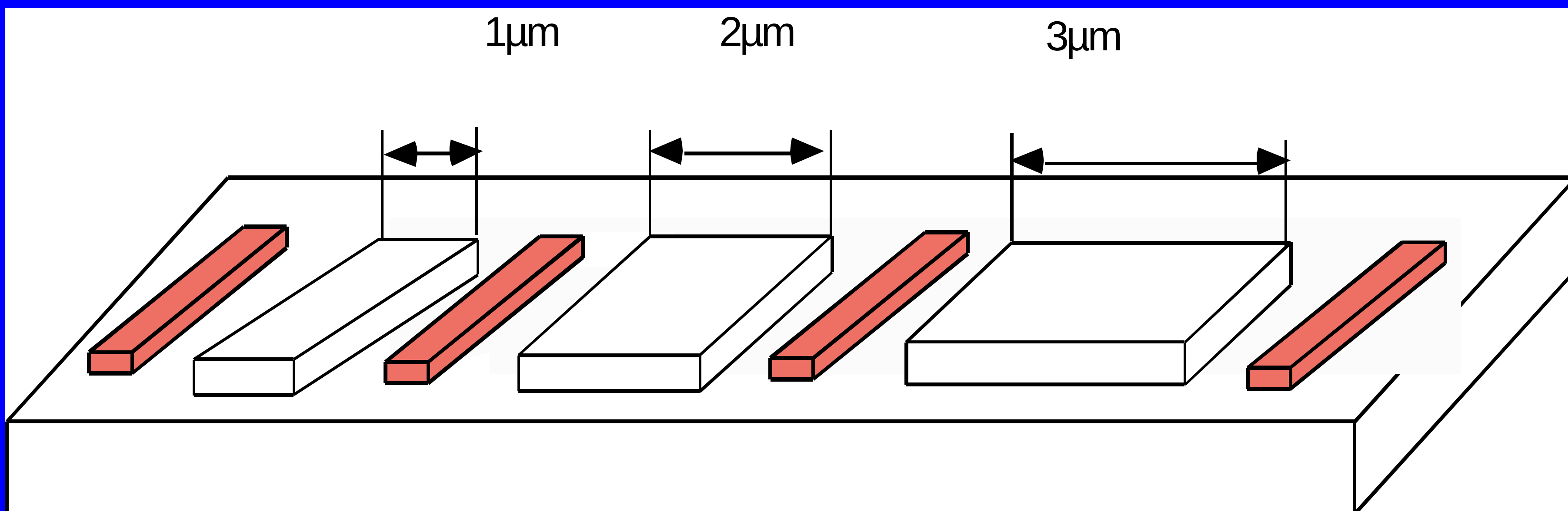
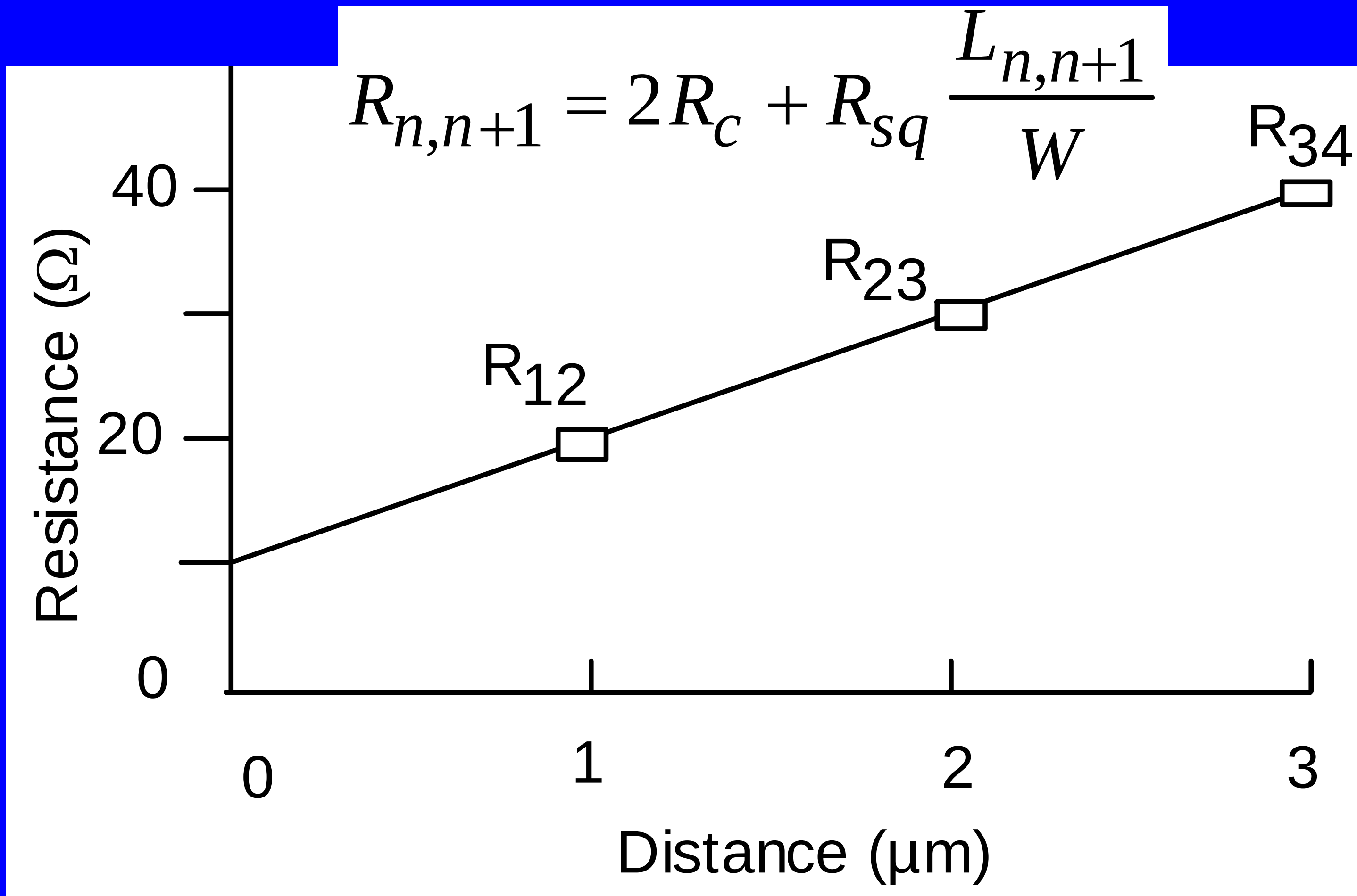
Sandwich and Planar Structures



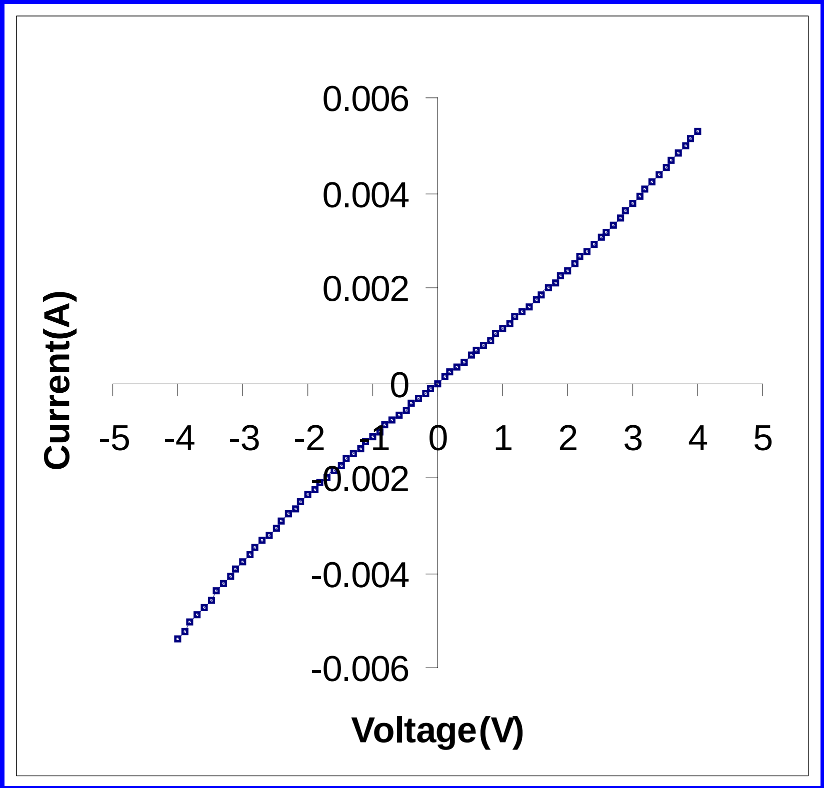
Gated Transmission Line Model

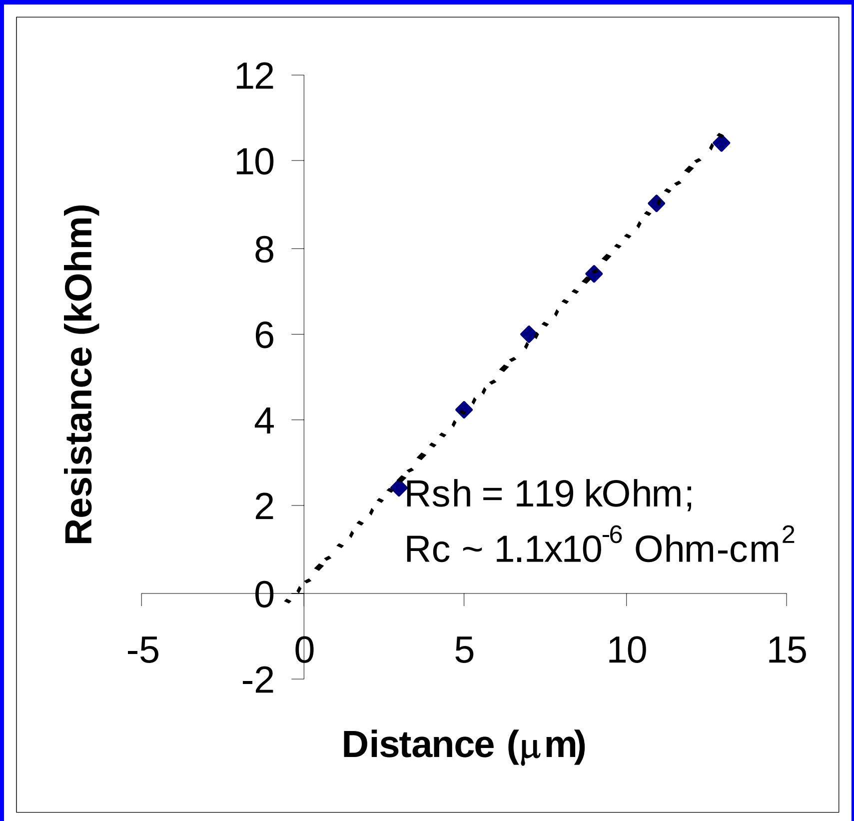


Resistance versus distance



I-V curve (a) and TLM plot (b) for annealed Pd/Ag/Au contact to p-GaN.





From V. Adivarahan, A. Lunev, M. Asif Khan, J. Yang, G. Simin, M. S. Shur, and R. Gaska, Very low specific resistance Pd/Ag/Au/Ti/Au alloyed ohmic contact to p-GaN for high current devices, Appl. Phys. Lett, 78, No. 18, pp. 2781-2783, April 30 (2001)

Example

The plot in the figure is for a pattern with contact width W = 50 μm. The film thickness, t, is 0.2 μm. From the data shown in the figure, determine the contact resistance, the resistance of the semiconductor film per square, the film conductivity, and the carrier concentration at room temperature (assume an n-type Si film).

Solution

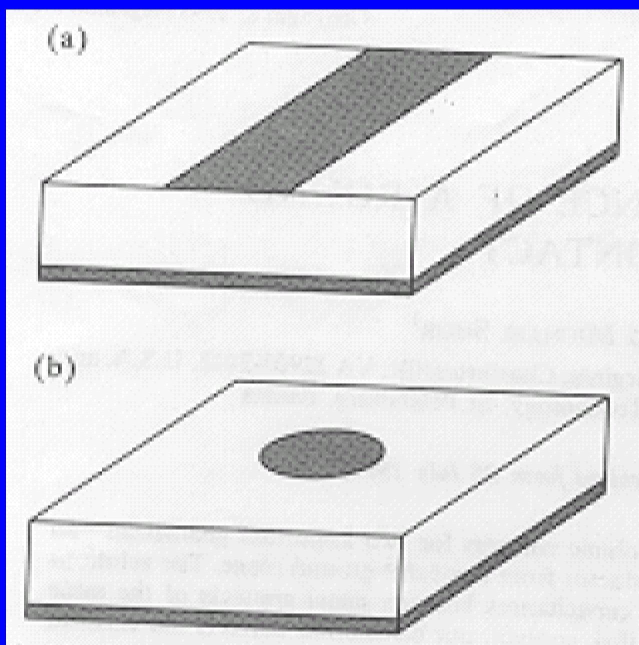
The resistance intercept is $2R_c = 10\ \Omega$. Hence, the contact resistance related to a 1 mm width, $R_{cm} = 0.25\ \Omega$mm. The slope $R_{sq}/W = 10\ \Omega/\mu$m. Hence, the film resistance per square, $R_{sq} = 10 \times 50 = 500\ \Omega$ per square. [The meaning of this notation (Ω per square) is that any square of this film has the same resistance independently of the square size.] The film conductivity

$$\sigma = 1/(R_{sq}t) = 1/(500 \times 0.2 \times 10^{-4}) = 100\ 1/\Omega\text{cm}$$

For an *n*-type silicon film at room temperature, the electron mobility $\mu_n \sim 1{,}000$ cm^2/Vs, this value of the conductivity corresponds to the electron carrier concentration, $n = \sigma/(q\mu_n) = 100/(1.602 \times 10^{-19} \times 1{,}000) = 6.24 \times 10^{17}$ cm^{-3}.

Fringe resistance and capacitance

$1/\rho \rightarrow \varepsilon$ $1/R_c \rightarrow C$



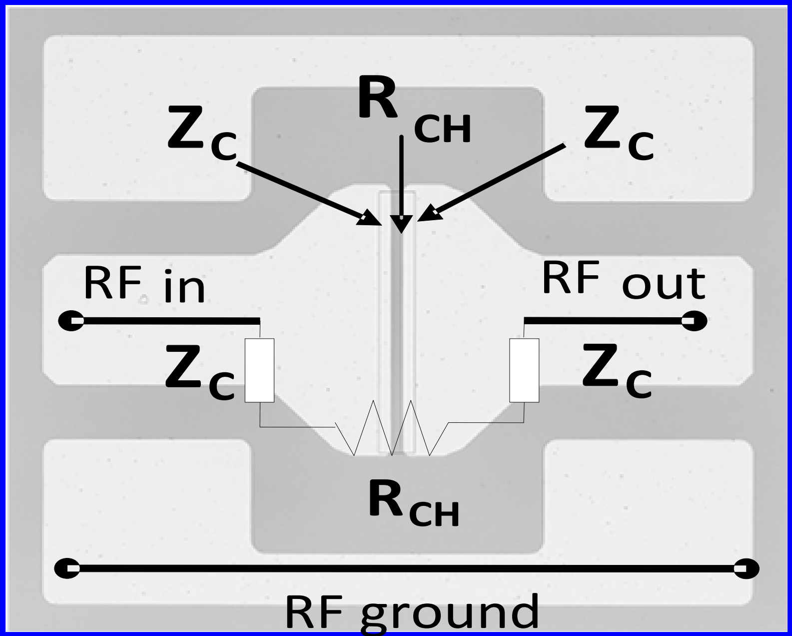
$$C_{edge} = \frac{2\varepsilon P \ln 2}{\pi} = 4\varepsilon a \ln 2.$$

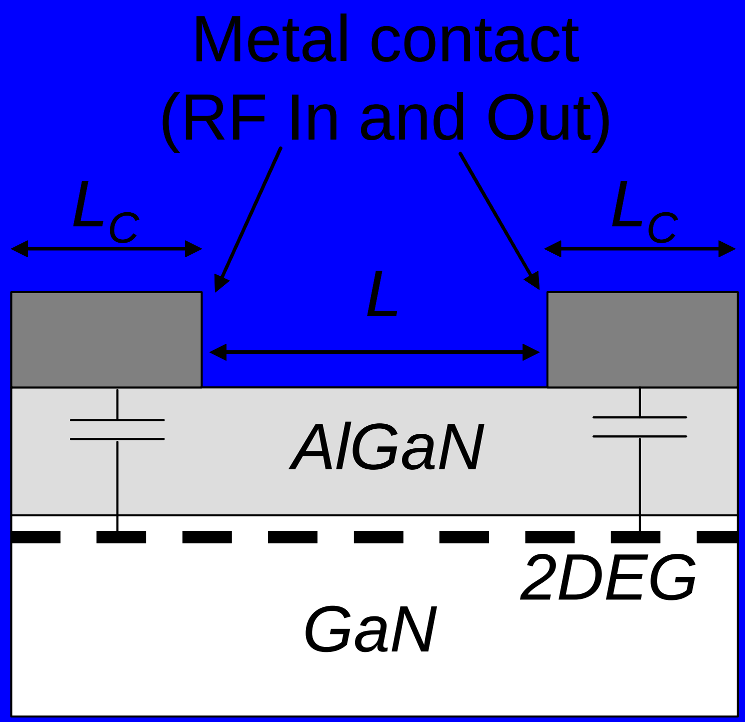
Fringing (edge) capacitance

From B. Gelmont and M. S. Shur, Spreading Resistance of a Round Ohmic Contact, Solid State Electronics, Vol. 36, No. 2, pp. 143-146 (1993)

RF TLM

Microphotograph

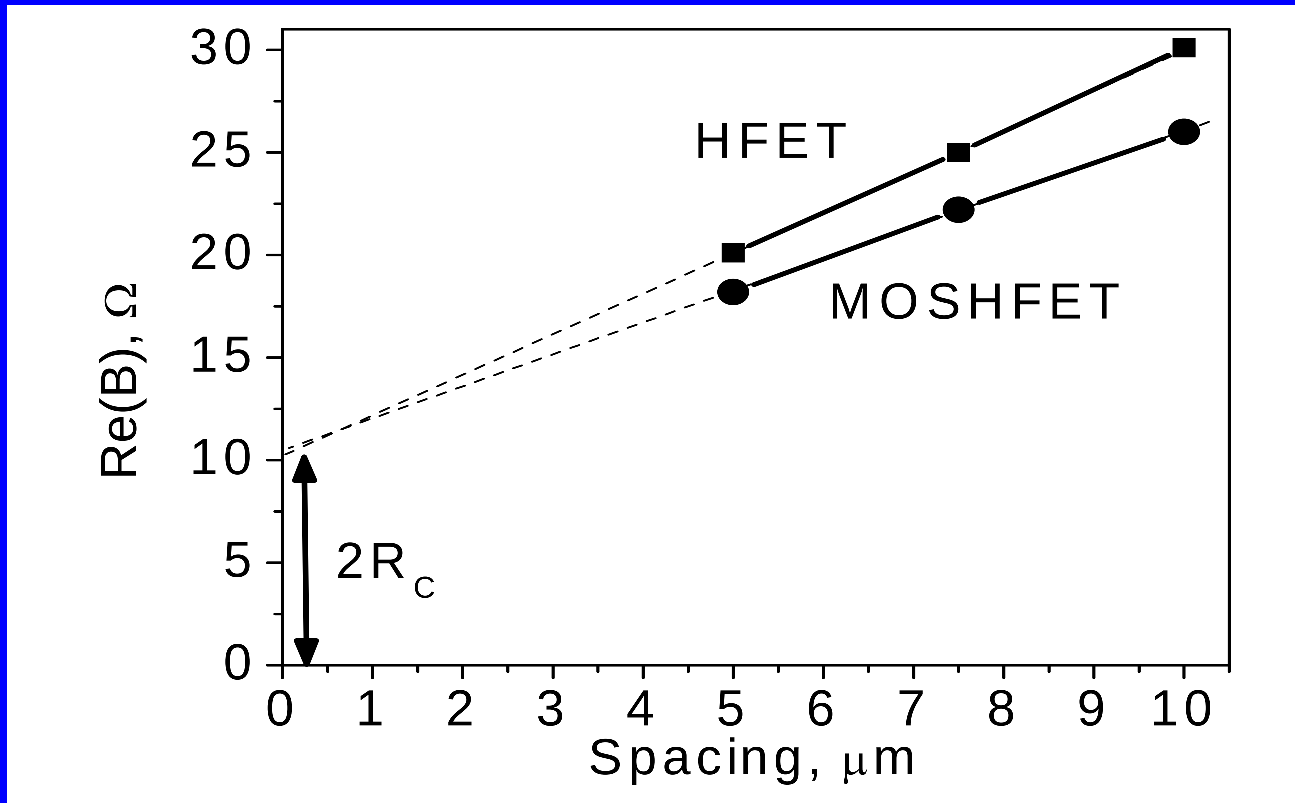




From A. Koudymov, N. Pala, V. Tokranov, S. Oktyabrsky, M. Gaevski, R. Jain, J. Yang, X. Hu, M. Shur, R. Gaska, G. Simin

RF Transmission Line Method for Wide Bandgap Heterostructures

RF TLM Results



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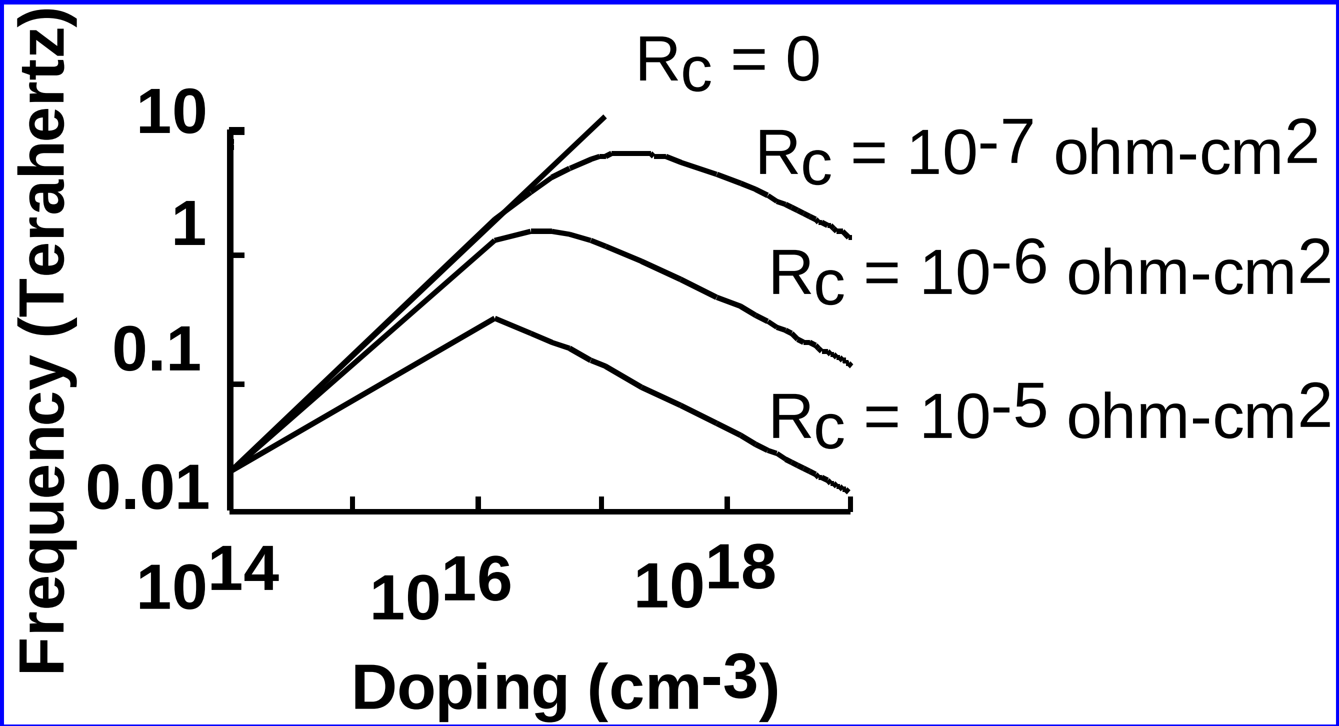
RF Transmission Line Method for Wide Bandgap Heterostructures

Ohmic Contacts. Summary.

Contact resistance for a sandwich structure	$R_c = \frac{\rho_c}{S}$
Contact resistance for a planar structure	$R_c = \frac{R_{cm}}{W}$
Resistance of TLM structure	$R_{n,n+1} = 2R_c + R_{sq}\frac{L_{n,n+1}}{W}$
Resistance of semiconductor film per square	$R_{sq} = \frac{1}{\sigma t}$

Effect of series resistance on Schottky diode cutoff frequency

$$f_t = 1/[2\pi C_d(R_s + R_c)]$$



Terahertz Schottky Diodes from Virginia Semiconductors, Inc.

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