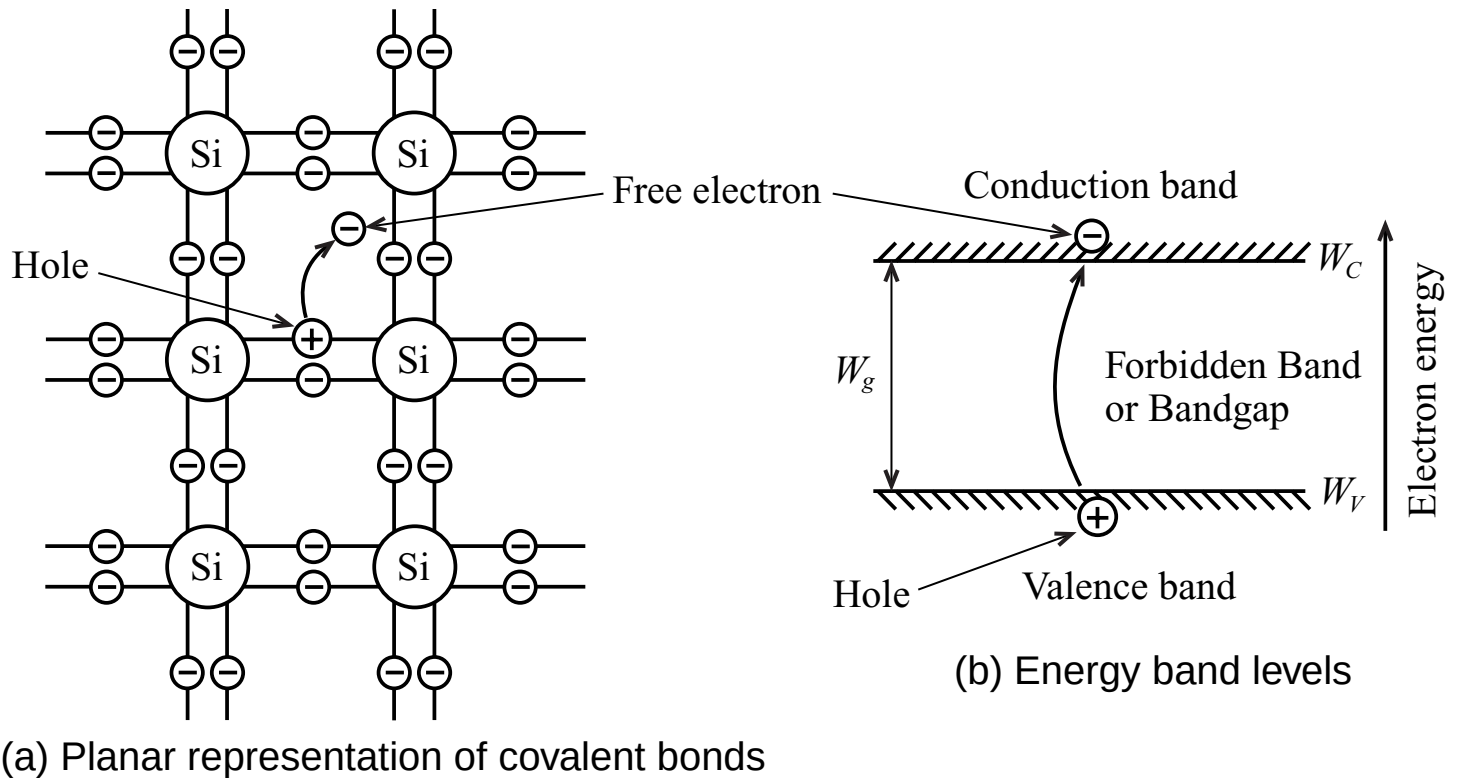


## FIGURES FOR CHAPTER 6



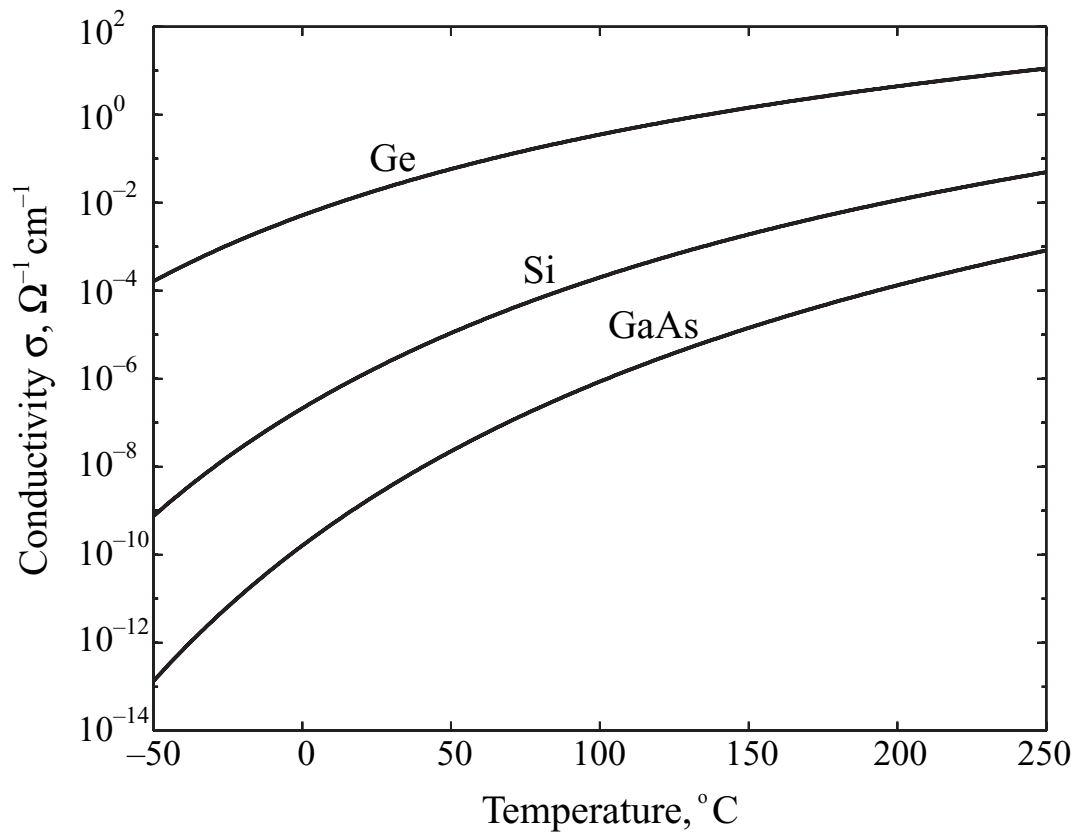
**Figure 6-1** Lattice structure and energy levels of silicon.

(a) schematic planar crystal arrangement with thermal breakup of one valent bond resulting in a hole and a moving electron for  $T > 0^\circ\text{K}$ .

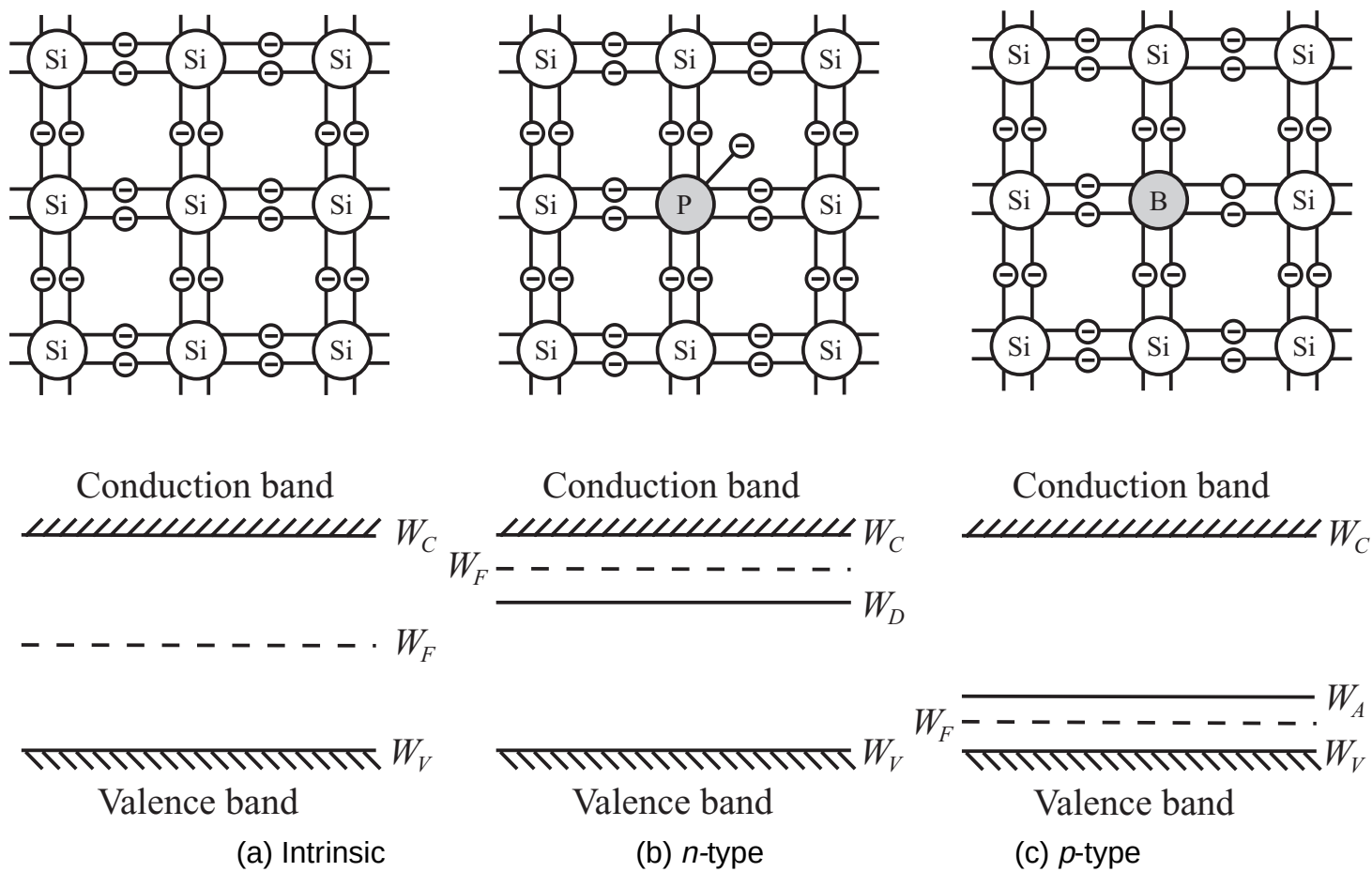
(b) equivalent energy band level representation whereby a hole is created in the valence band  $W_V$  and an electron is produced in the conduction band  $W_C$ . The energy gap between both bands is indicated by  $W_g$ .

**Table 6-1** Effective concentrations and effective mass values at  $T = 300^\circ\text{K}$ 

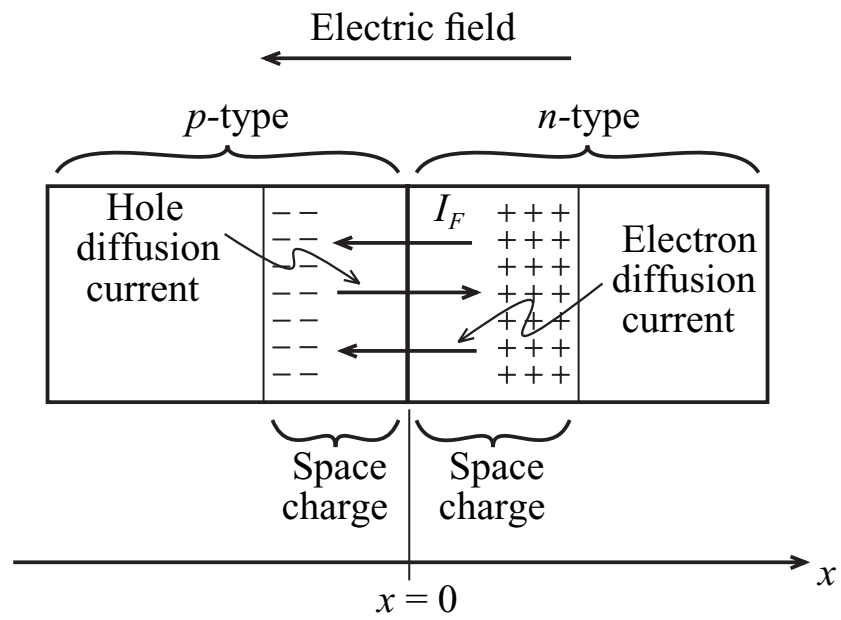
| Semiconductor           | $m_n^*/m_0$ | $m_p^*/m_0$ | $N_C(\text{cm}^{-3})$ | $N_V(\text{cm}^{-3})$ | $n_i(\text{cm}^{-3})$ |
|-------------------------|-------------|-------------|-----------------------|-----------------------|-----------------------|
| Silicon (Si)            | 1.08        | 0.56        | $2.8 \times 10^{19}$  | $1.04 \times 10^{19}$ | $1.45 \times 10^{10}$ |
| Germanium (Ge)          | 0.55        | 0.37        | $1.04 \times 10^{19}$ | $6.0 \times 10^{18}$  | $2.4 \times 10^{13}$  |
| Gallium Arsenide (GaAs) | 0.067       | 0.48        | $4.7 \times 10^{17}$  | $7.0 \times 10^{18}$  | $1.79 \times 10^6$    |



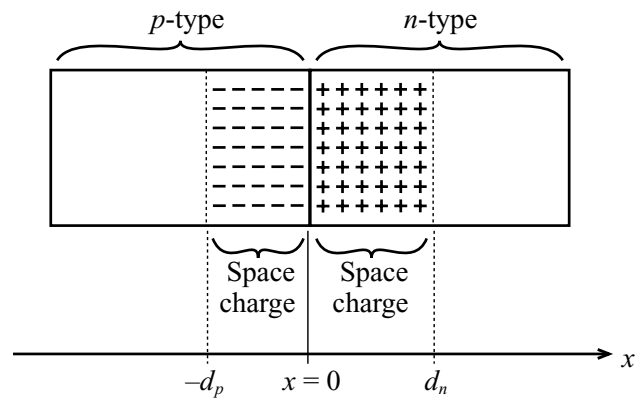
**Figure 6-2** Conductivity of Si, Ge, GaAs in the range from  $-50^{\circ}\text{C}$  to  $250^{\circ}\text{C}$ .



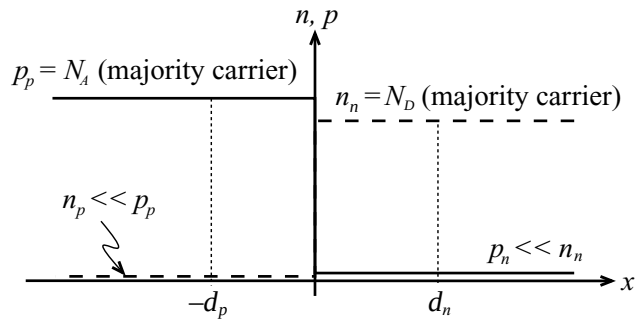
**Figure 6-3** Lattice structure and energy band model for (a) intrinsic, (b) *n*-type, and (c) *p*-type semiconductors at no thermal energy.  $W_D$  and  $W_A$  are donor and acceptor energy levels.



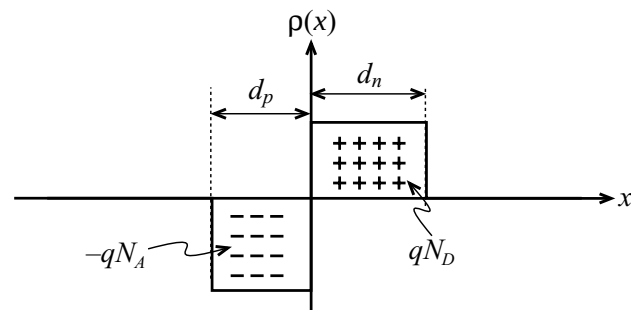
**Figure 6-4** Current flow in the  $pn$ -junction



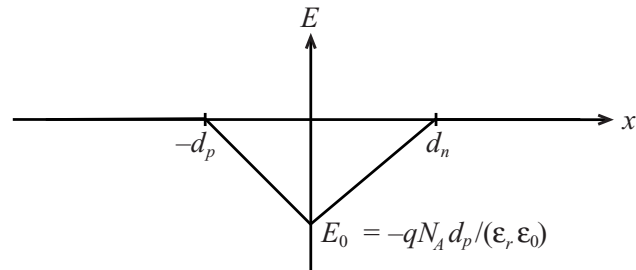
(a)  $pn$ -junction with space charge extent



(b) Acceptor and donor concentrations

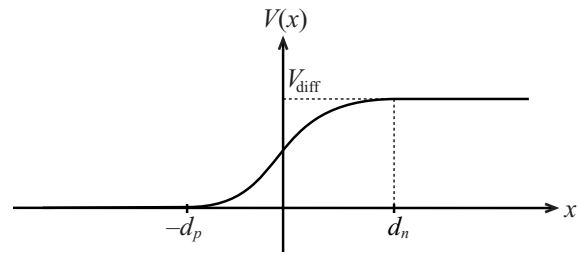


(c) Polarity of charge density distribution



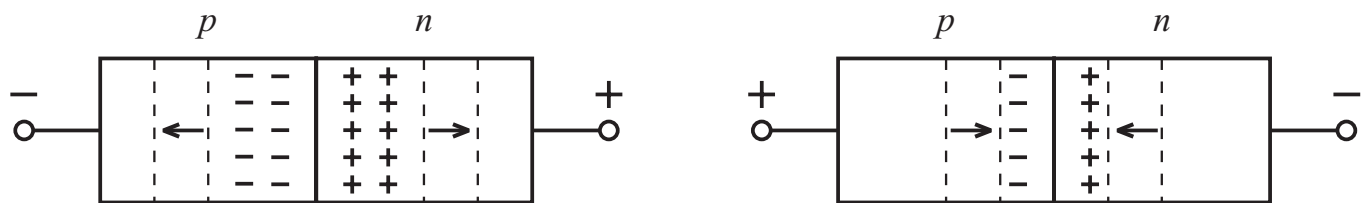
(d) Electric field distribution

**Figure 6-5** The  $pn$ -junction with abrupt charge carrier transition in the absence of an externally applied voltage.

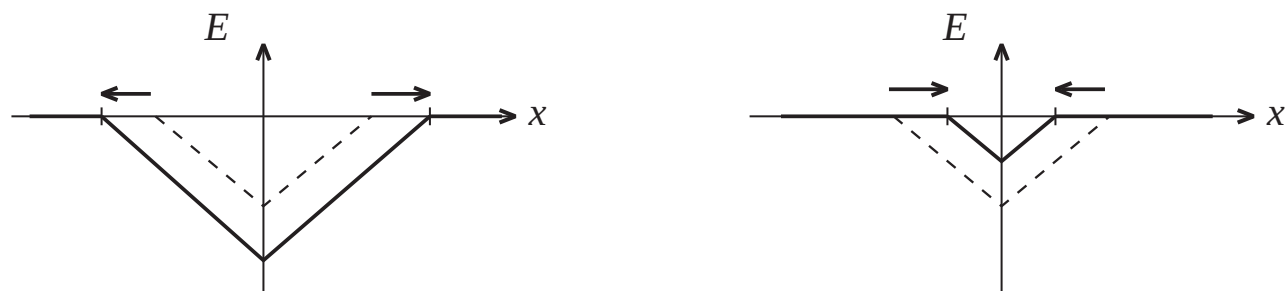


(e) Barrier voltage distribution

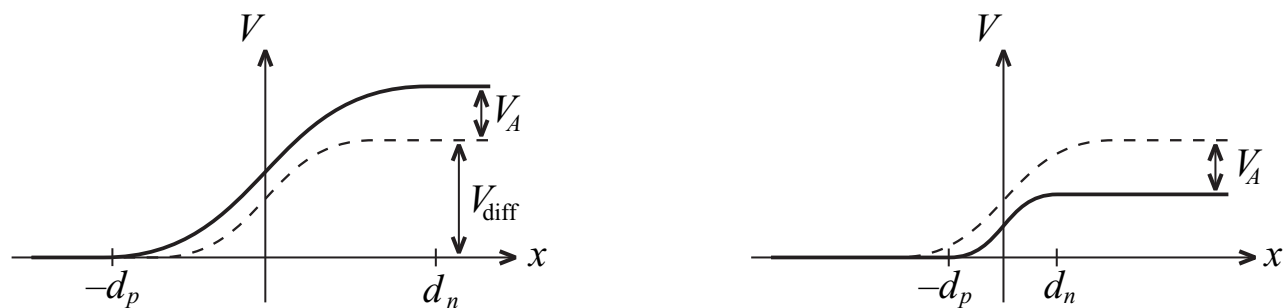
**Figure 6-5** The  $pn$ -junction with abrupt charge carrier transition in the absence of an externally applied voltage. (Continued)



Space charge distribution in the  $pn$ -junction



Electric field distribution in the  $pn$ -junction

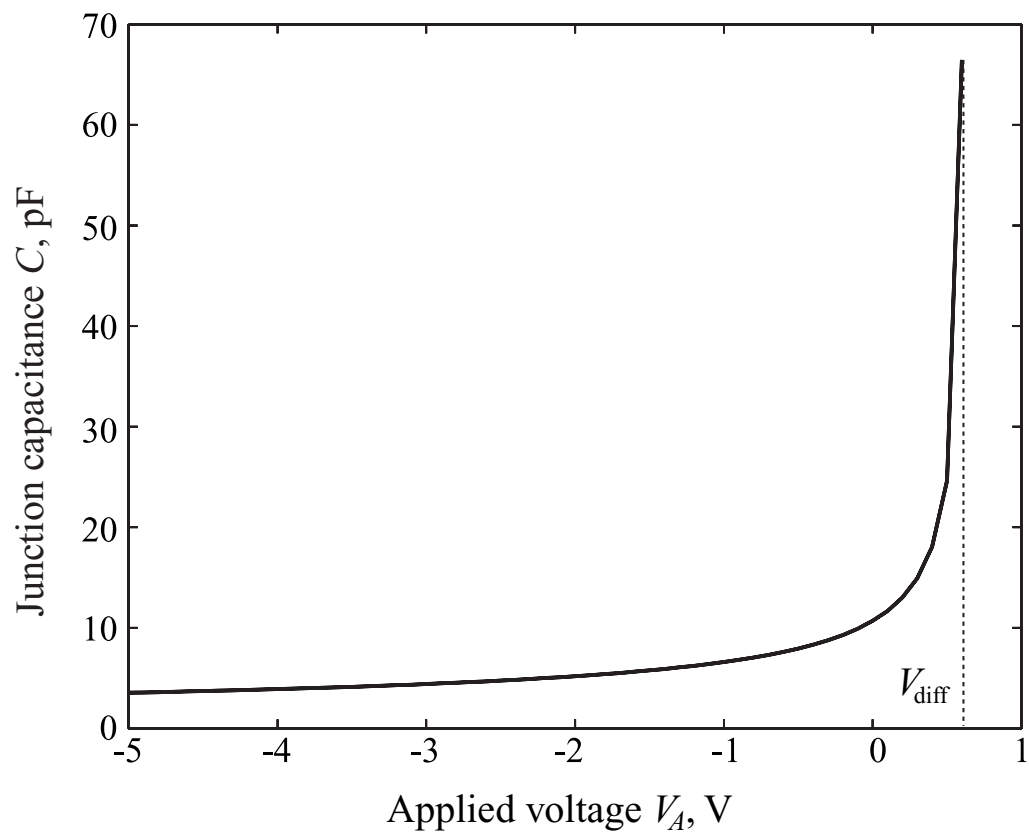


Voltage distribution in the  $pn$ -junction

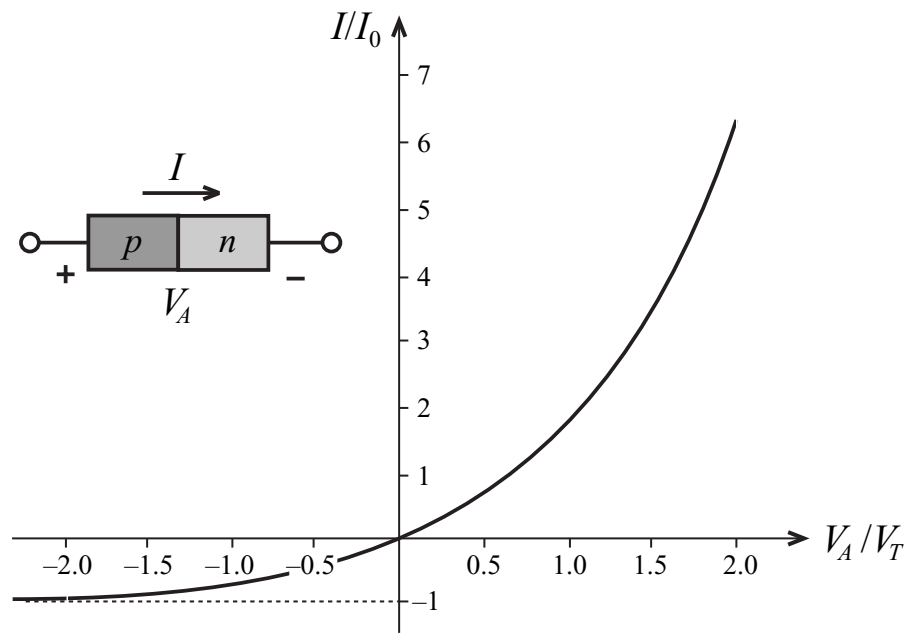
(a) Reverse biasing ( $V_A < 0$ )

(b) Forward biasing ( $V_A > 0$ )

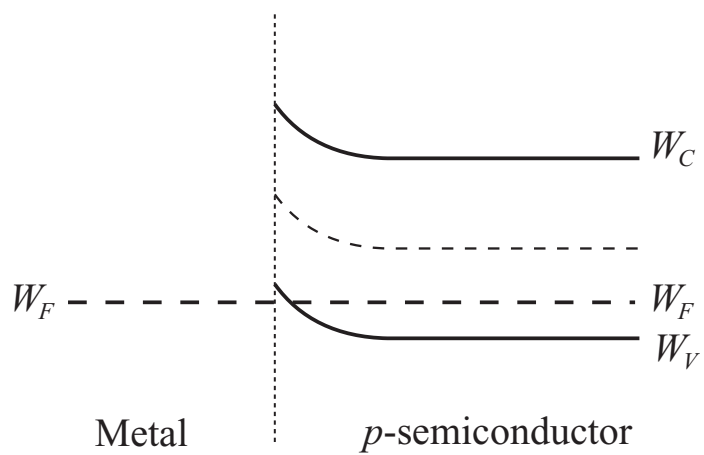
**Figure 6-6** External voltage applied to the  $pn$ -junction in reverse and forward directions.



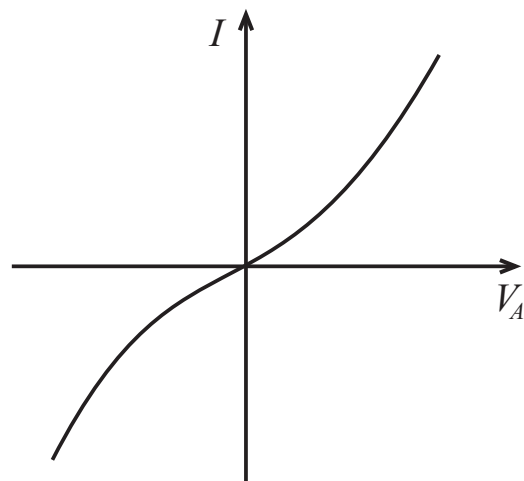
**Figure 6-7** The  $pn$ -junction capacitance as a function of applied voltage.



**Figure 6-8** Current-voltage behavior of  $pn$ -junction based on Shockley equation.

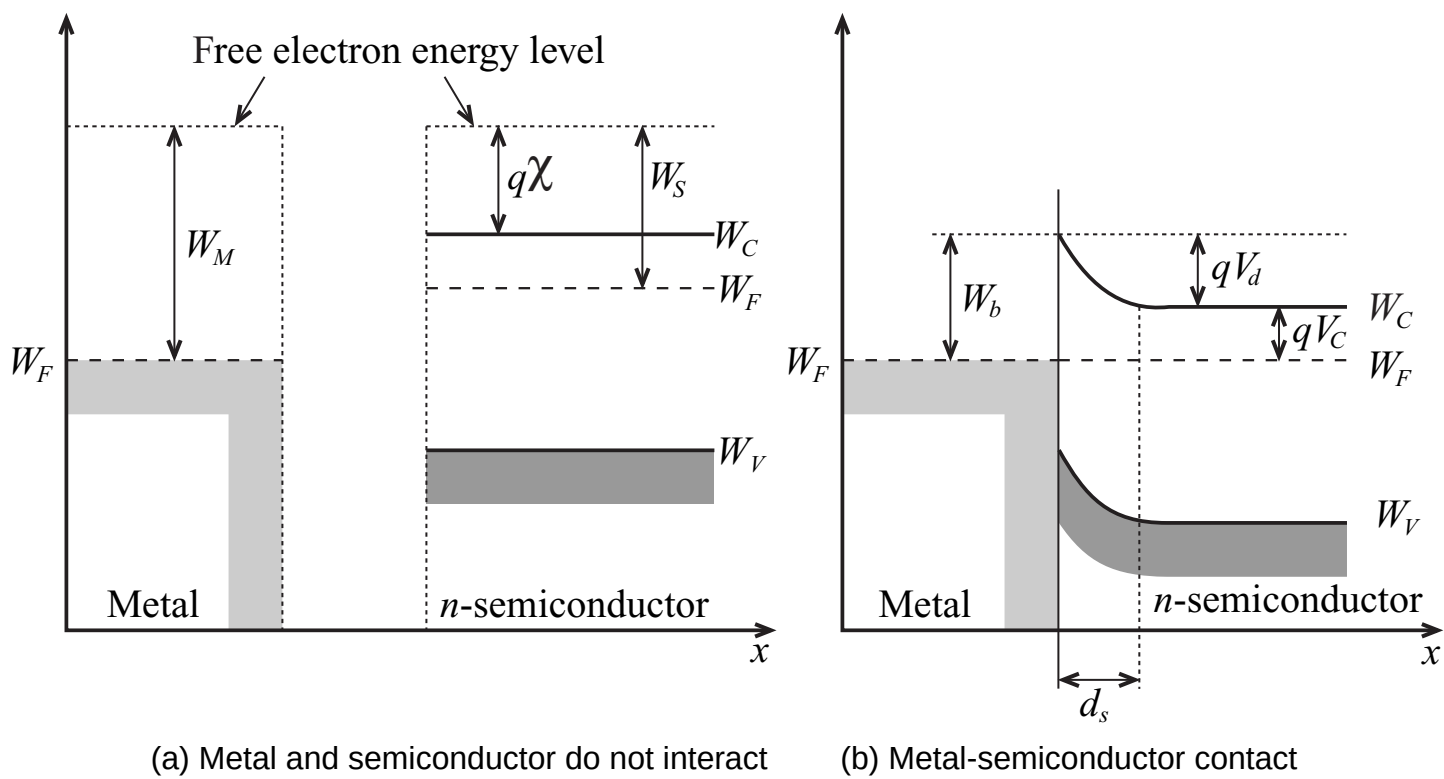


(a) Energy band model



(b) Voltage-current characteristic

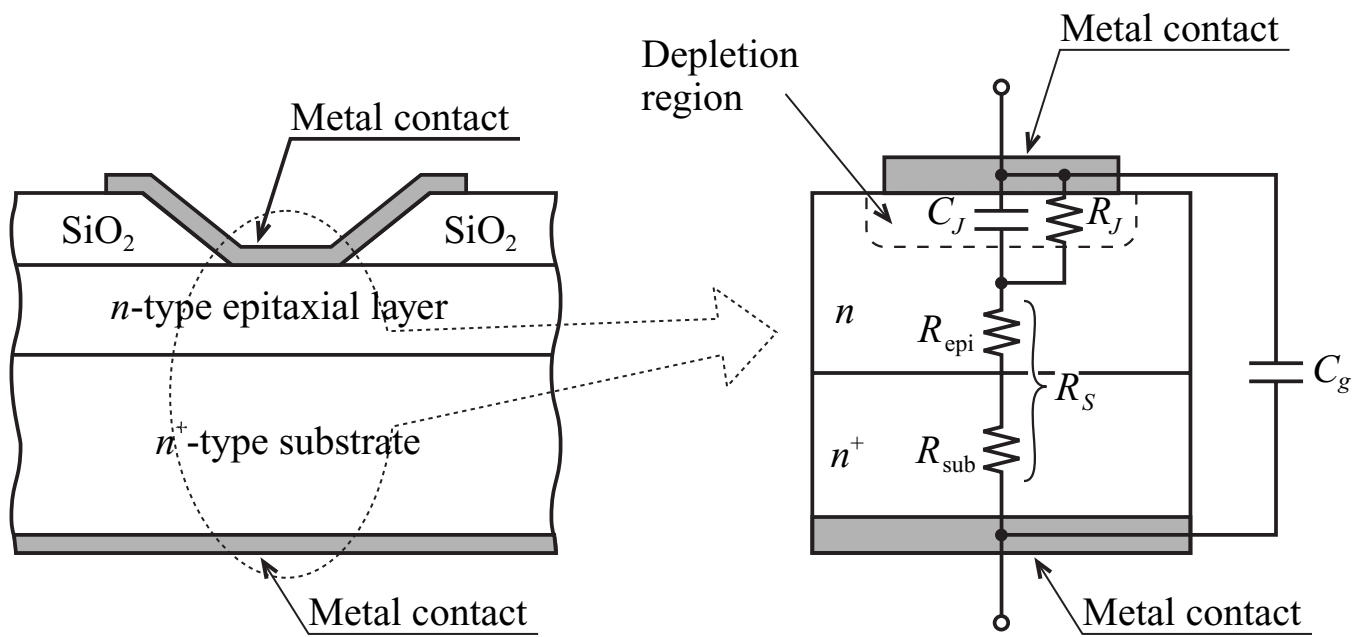
**Figure 6-9** Metal electrode in contact with  $p$ -semiconductor.



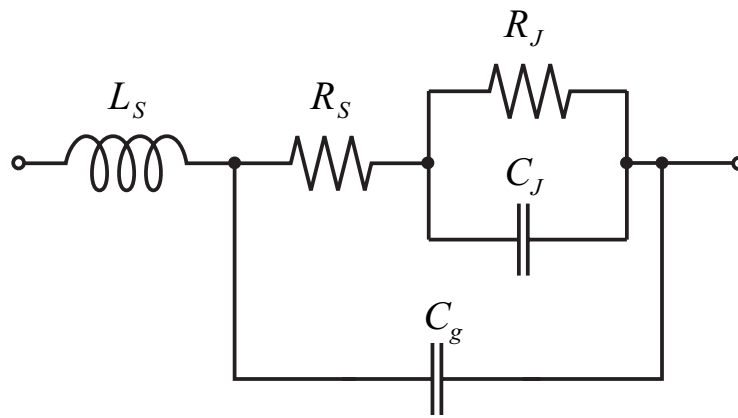
**Figure 6-10** Energy-band diagram of Schottky contact, (a) before and (b) after contact.

**Table 6-2** Work function potentials of some metals

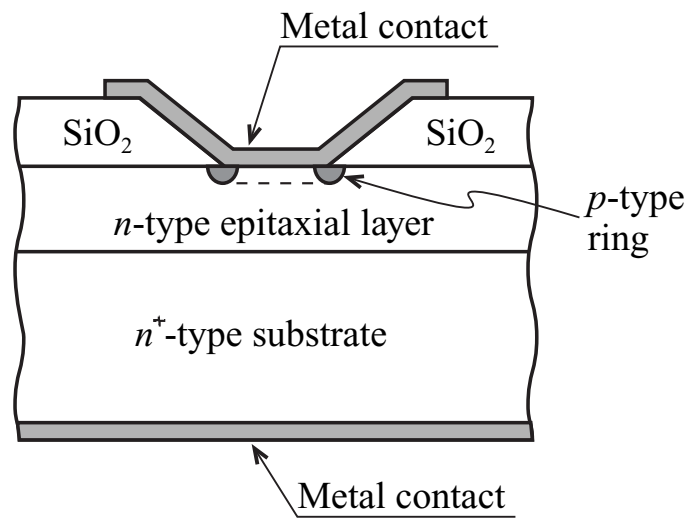
| Material        | Work function potential, $V_M$ |
|-----------------|--------------------------------|
| Silver (Ag)     | 4.26 V                         |
| Aluminum (Al)   | 4.28 V                         |
| Gold (Au)       | 5.1 V                          |
| Chromium (Cr)   | 4.5 V                          |
| Molybdenum (Mo) | 4.6 V                          |
| Nickel (Ni)     | 5.15 V                         |
| Palladium (Pd)  | 5.12 V                         |
| Platinum (Pt)   | 5.65 V                         |
| Titanium (Ti)   | 4.33 V                         |



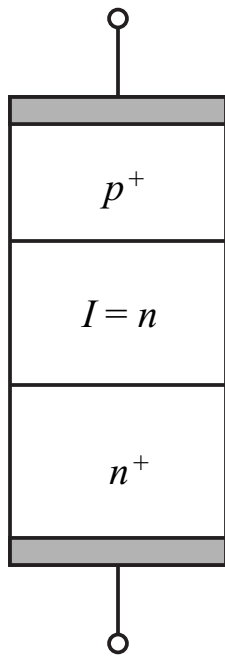
**Figure 6-11** Cross-sectional view of Si Schottky diode.



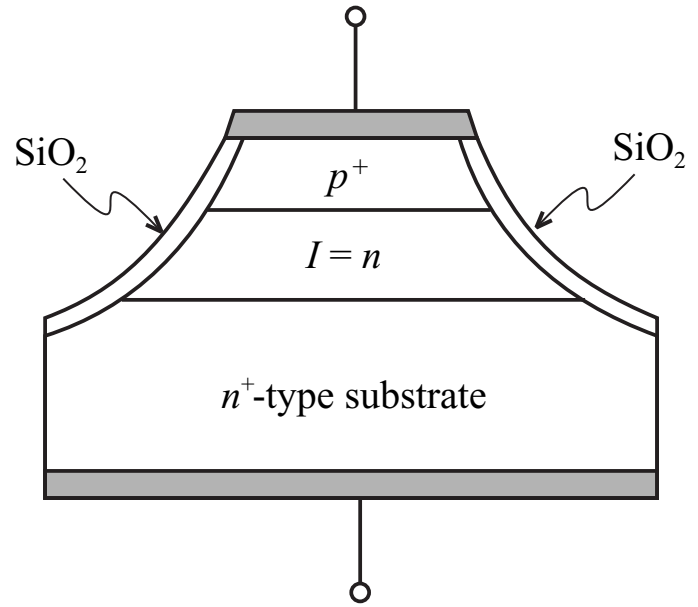
**Figure 6-12** Circuit model of typical Schottky diode.



**Figure 6-13** Schottky diode with additional isolation ring suitable for very-high-frequency applications.

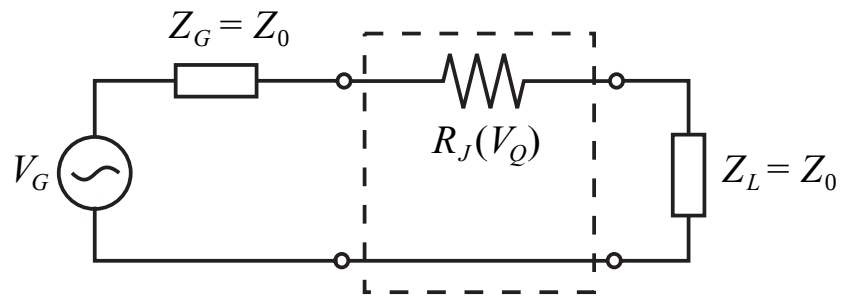


(a) Simplified structure of a PIN diode

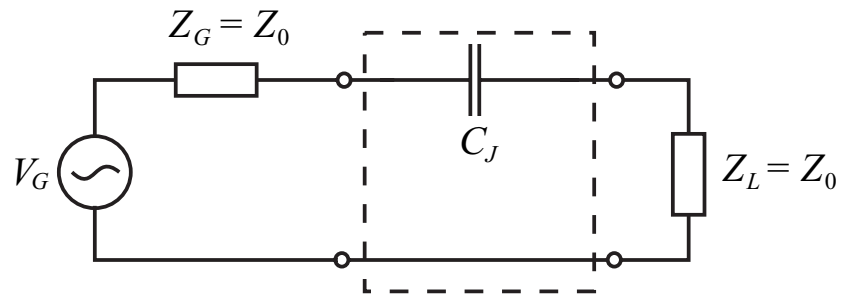


(b) Fabrication in mesa processing technology

**Figure 6-14** PIN diode construction.

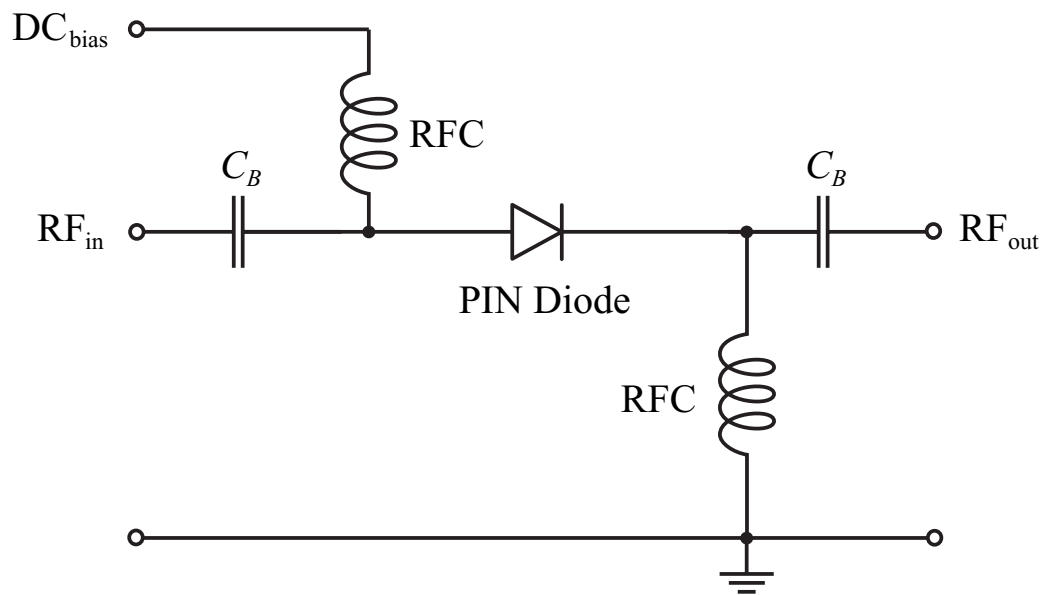


(a) Forward bias

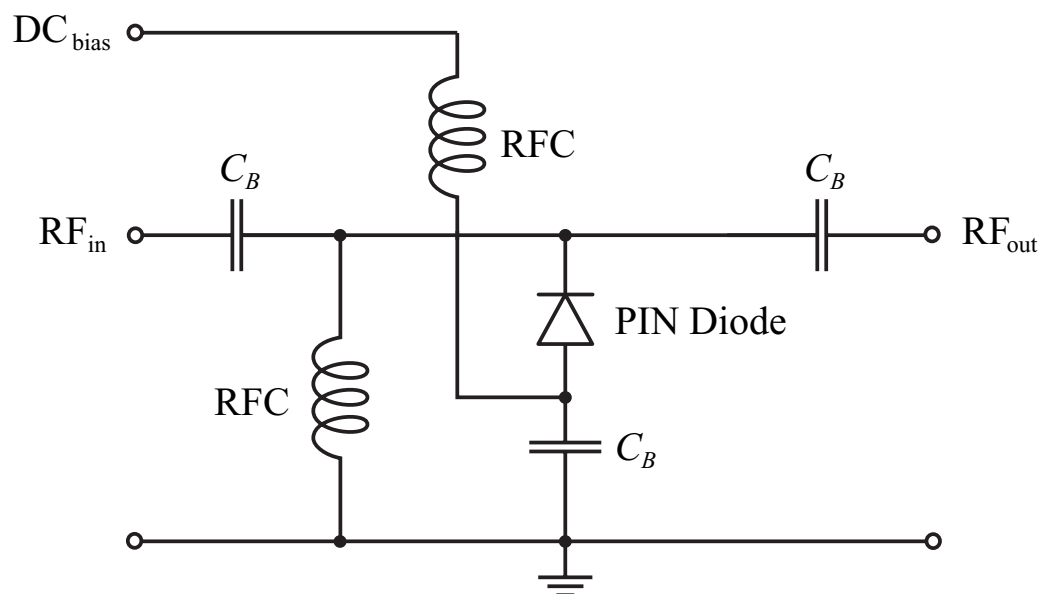


(b) Reverse bias (isolation)

**Figure 6-15** PIN diode in series connection.

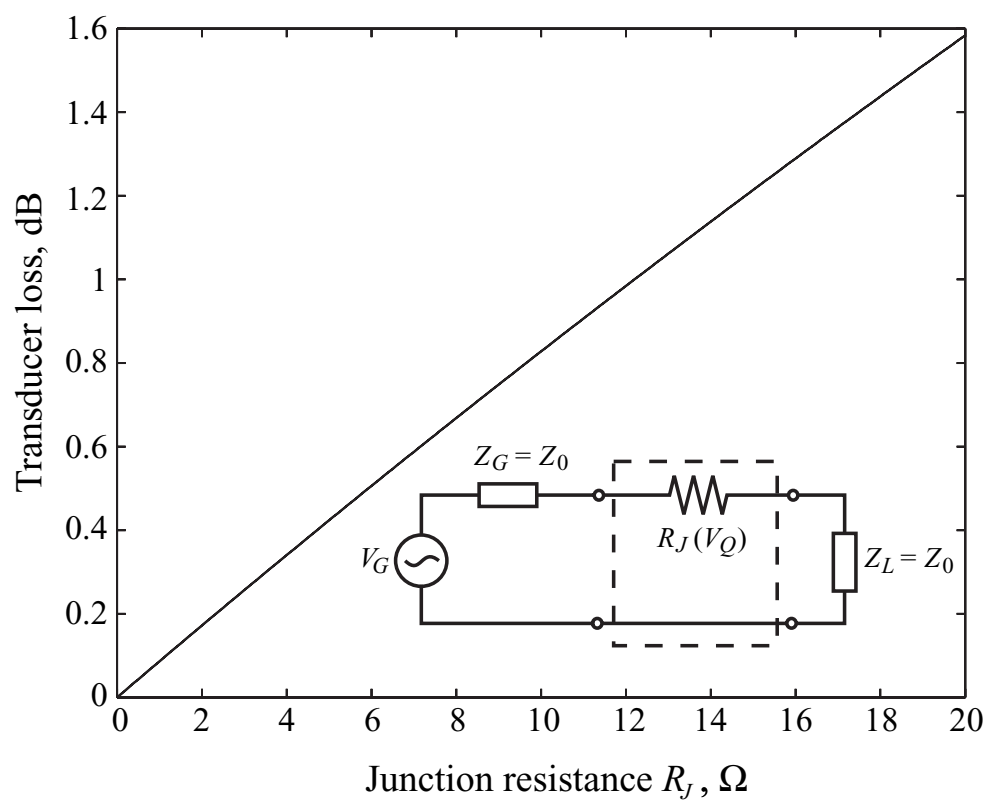


(a) Series connection of PIN diode

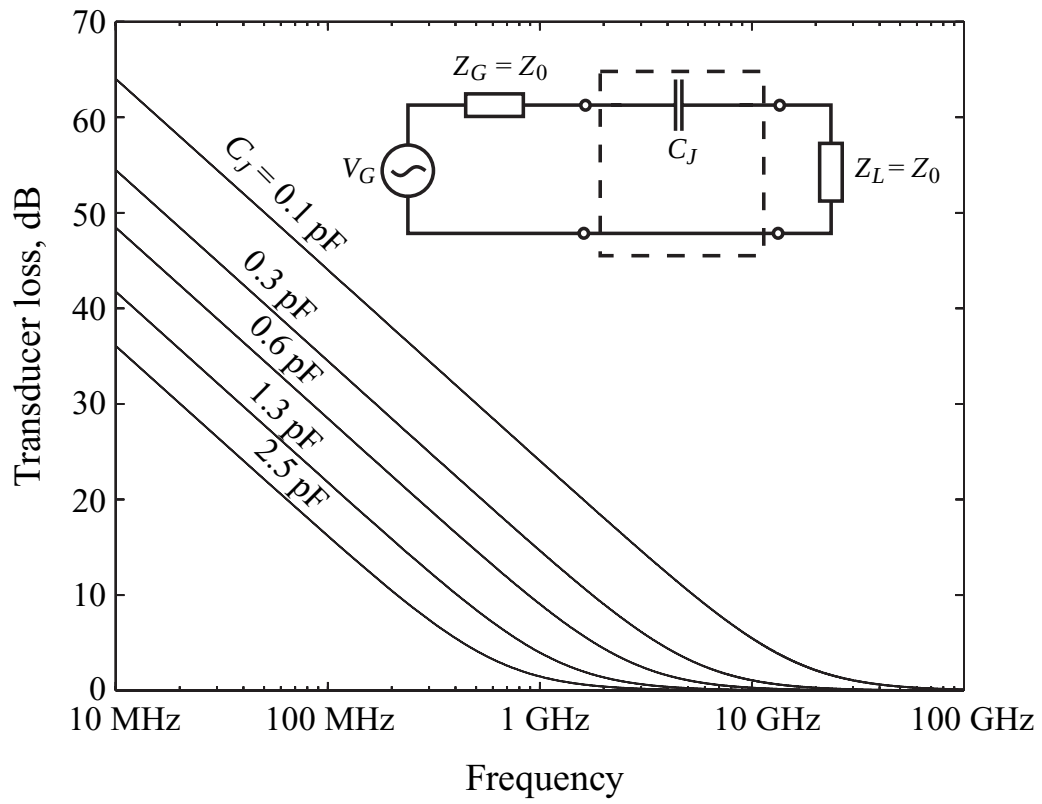


(b) Shunt connection of PIN diode

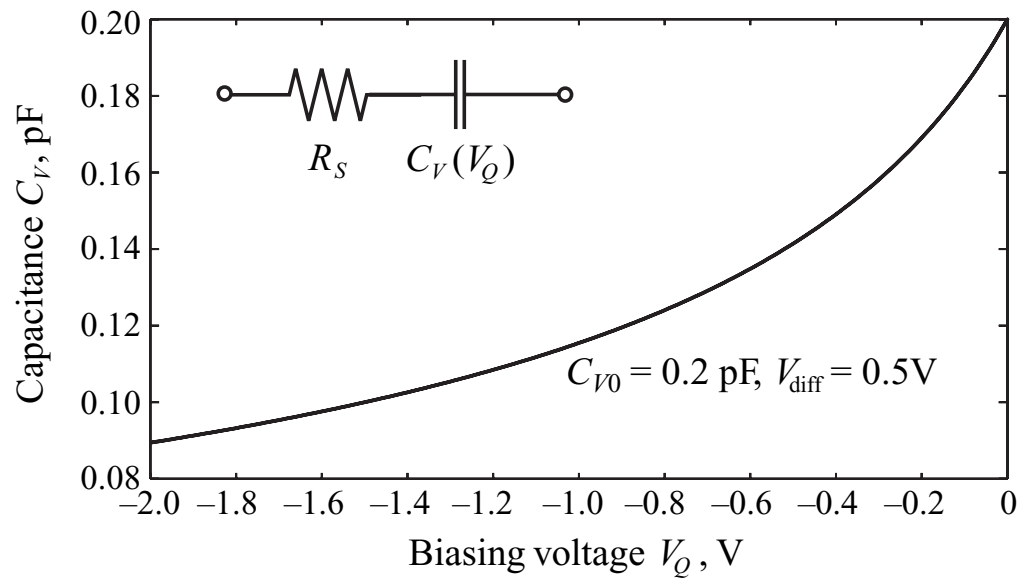
**Figure 6-16** Attenuator circuit with biased PIN diode in series and shunt configurations.



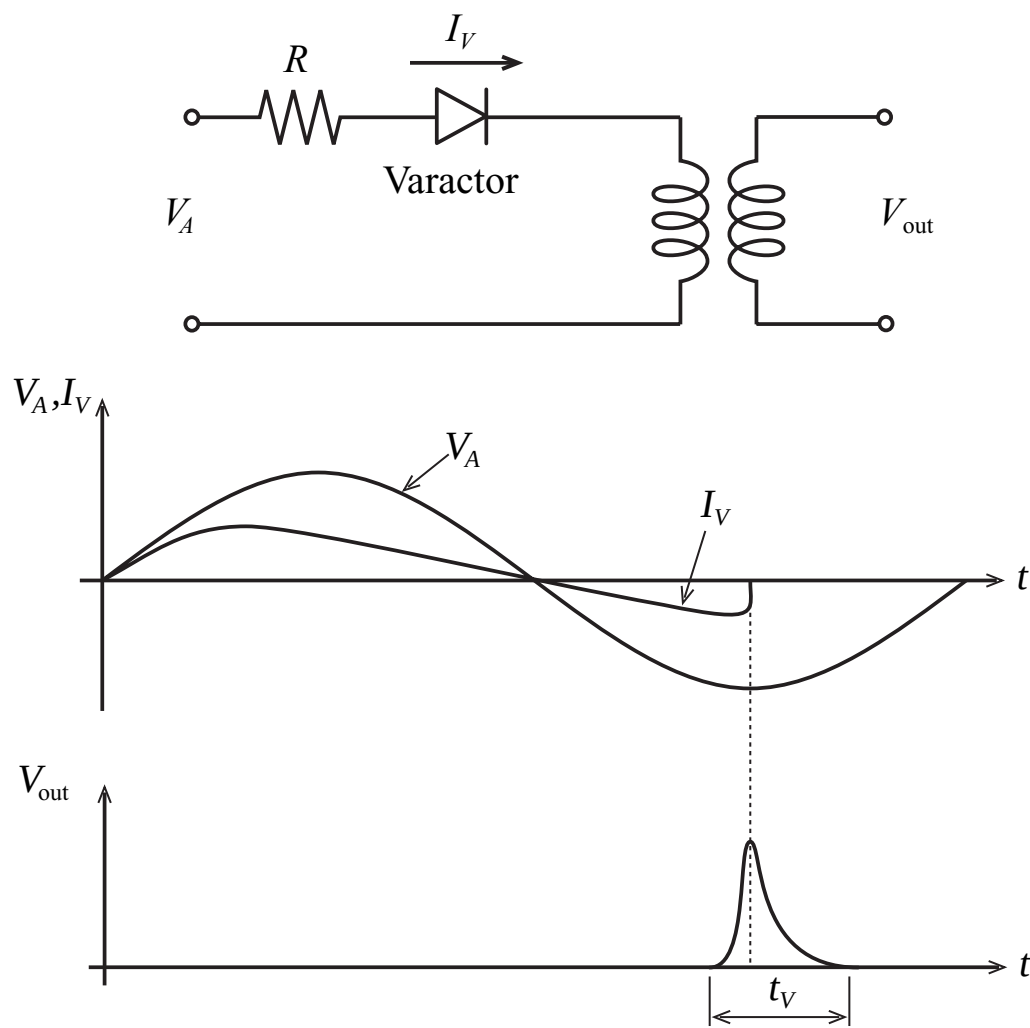
**Figure 6-17** Transducer loss of series connected PIN diode under forward bias condition. The diode behaves as a resistor.



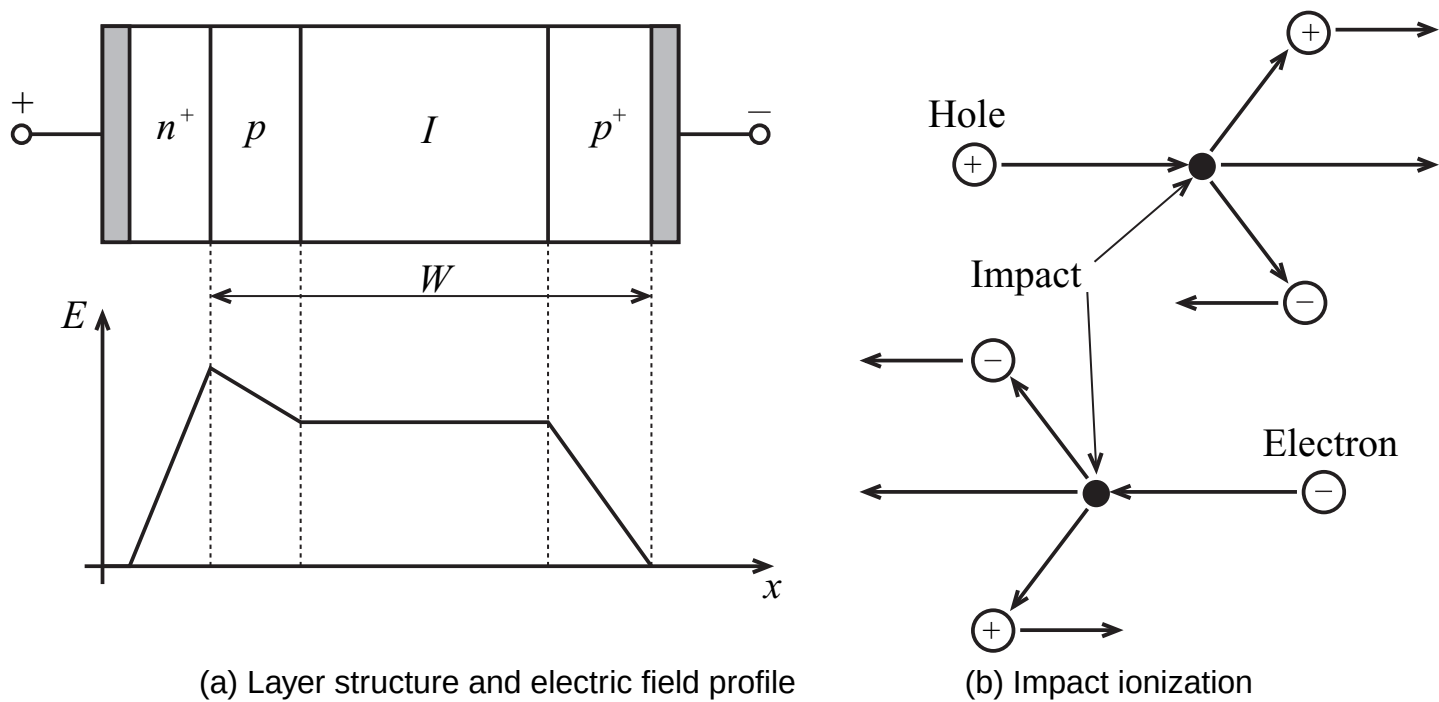
**Figure 6-18** Transducer loss of series connected PIN diode under reverse bias condition. The diode behaves as a capacitor.



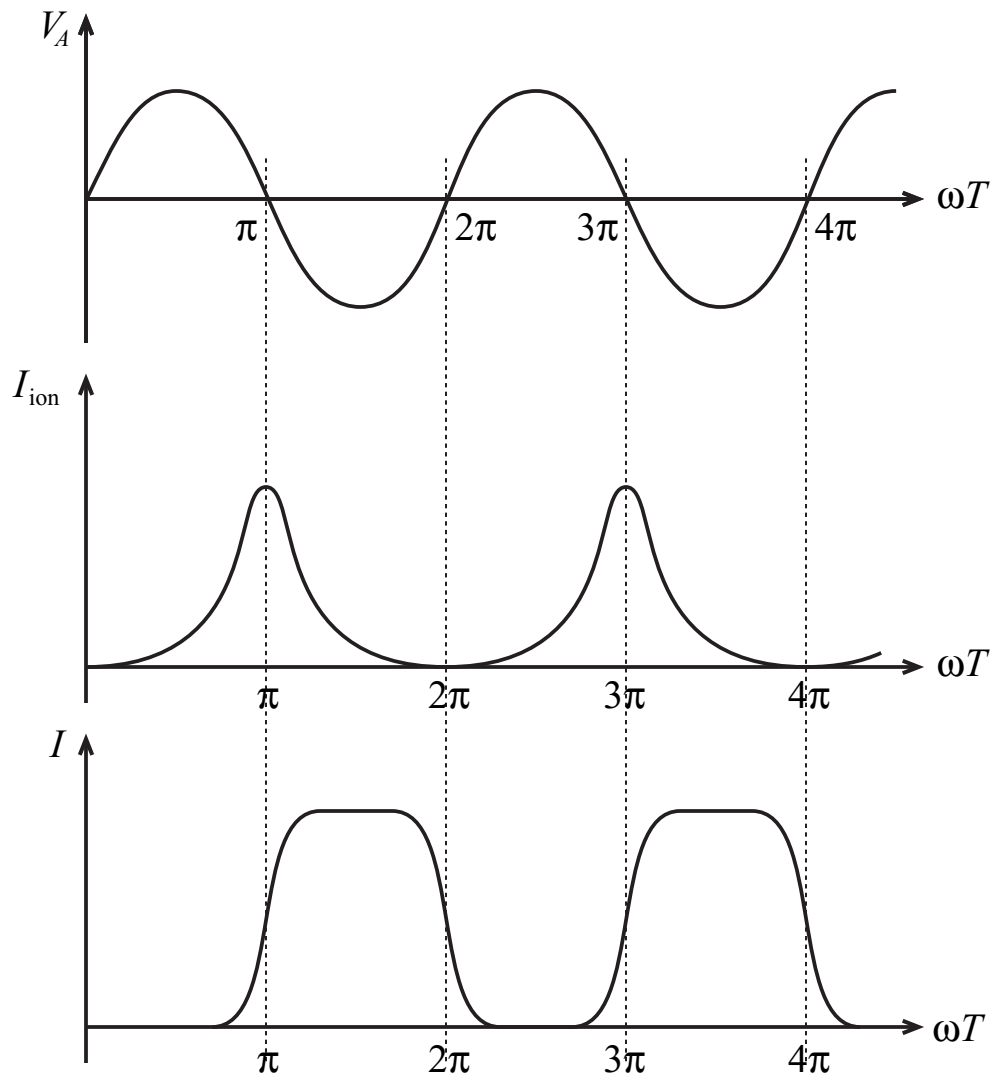
**Figure 6-19** Simplified electric circuit model and capacitance behavior of varactor diode.



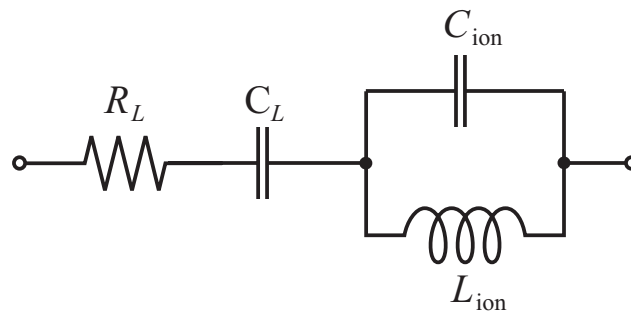
**Figure 6-20** Pulse generation with a varactor diode.



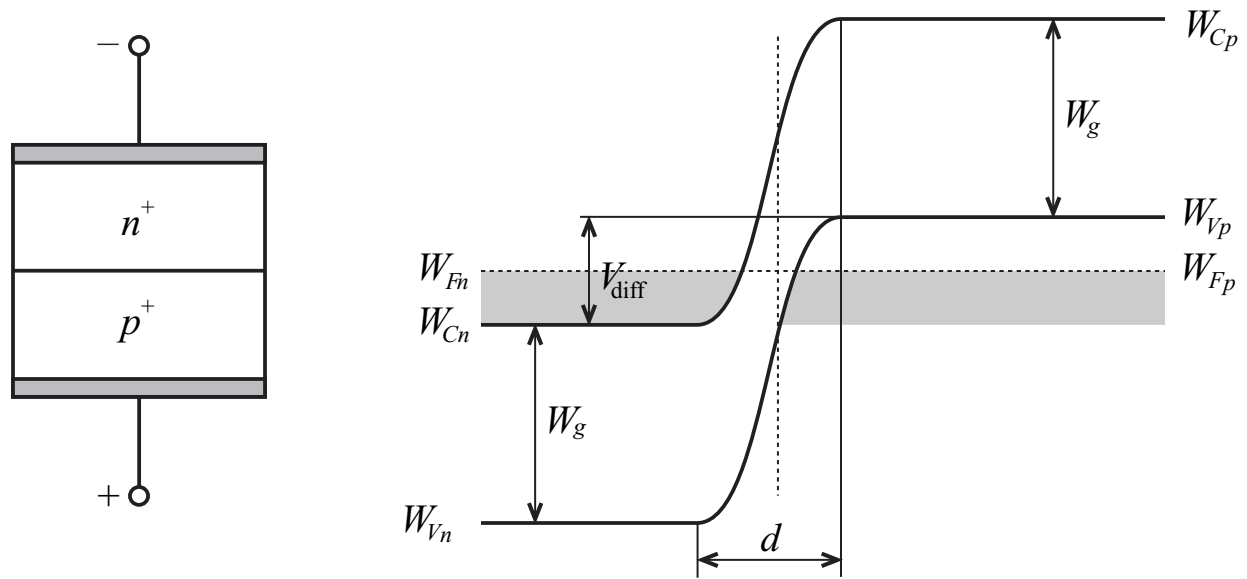
**Figure 6-21** IMPATT diode behavior.



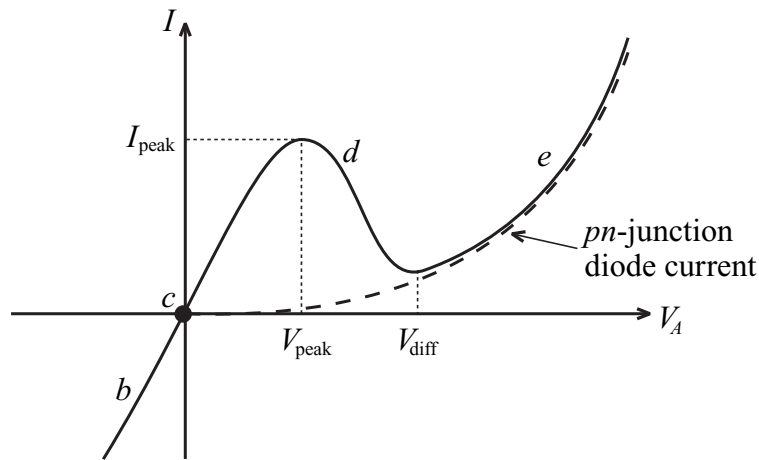
**Figure 6-22** Applied voltage, ionization current, and total current of an IMPATT diode.



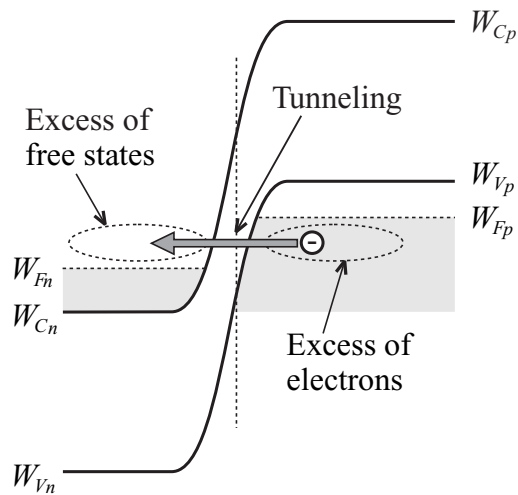
**Figure 6-23** Electric circuit representation for the IMPATT diode.



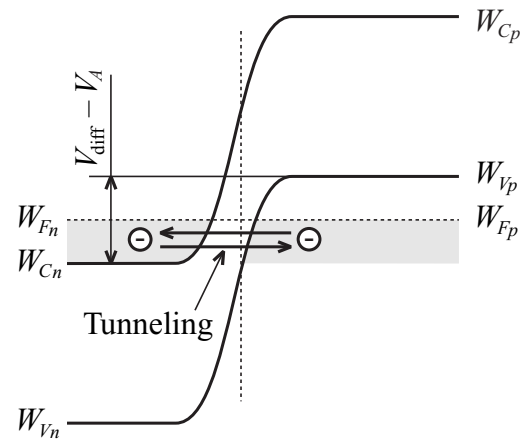
**Figure 6-24** Tunnel diode and its band energy representation.



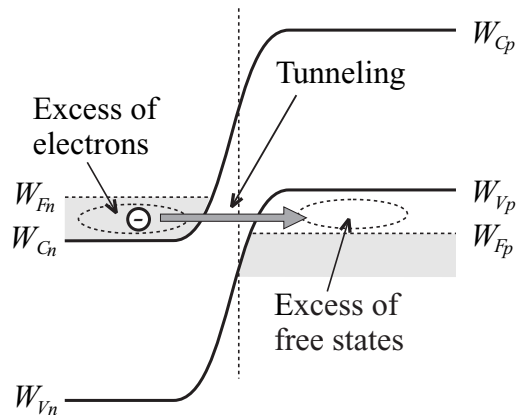
(a)  $I$ - $V$  curve of tunnel diode. At high positive biasing voltages the corresponding current of the tunnel diode approaches the current of the conventional  $pn$ -junction diode.



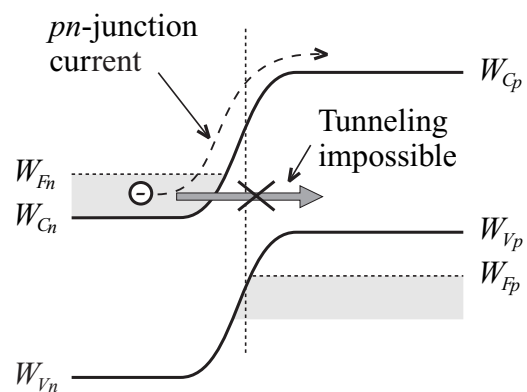
(b) Negative current flow for  $V_A < 0$



(c) No current flow for  $V_A = 0$

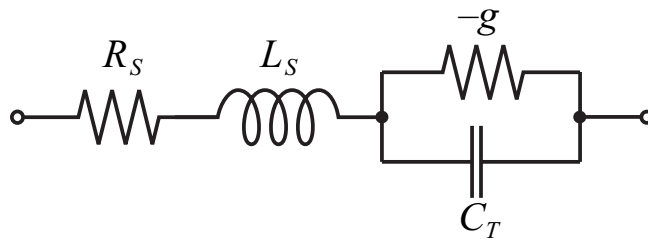


(d) Positive tunneling current,  $0 < V_A < V_{\text{diff}}$

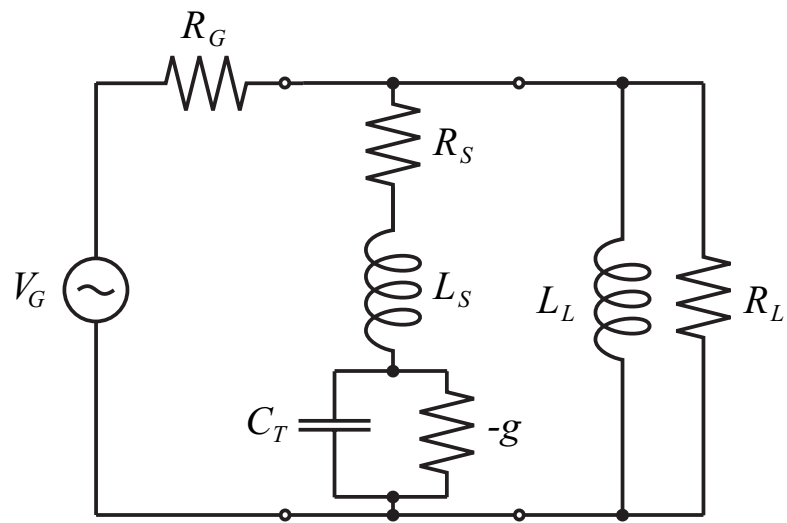


(e) Positive current flow for  $V_A > V_{\text{diff}}$

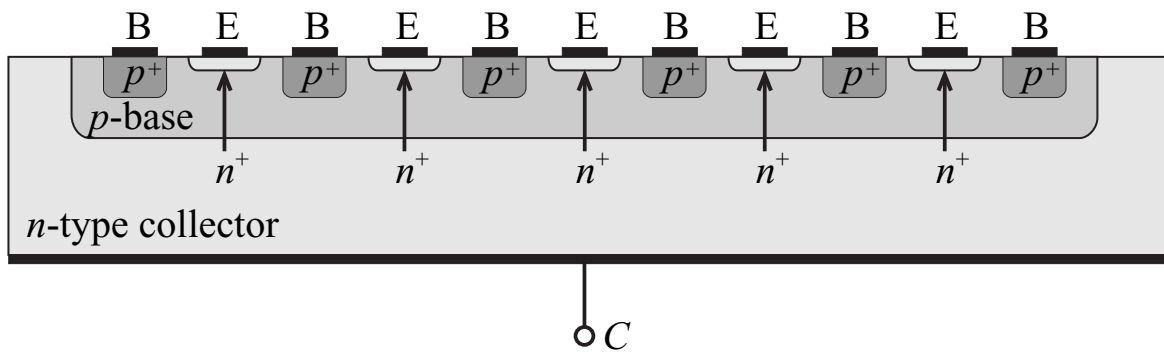
**Figure 6-25** Current-voltage behavior of the tunnel diode and comparison with energy band structure.



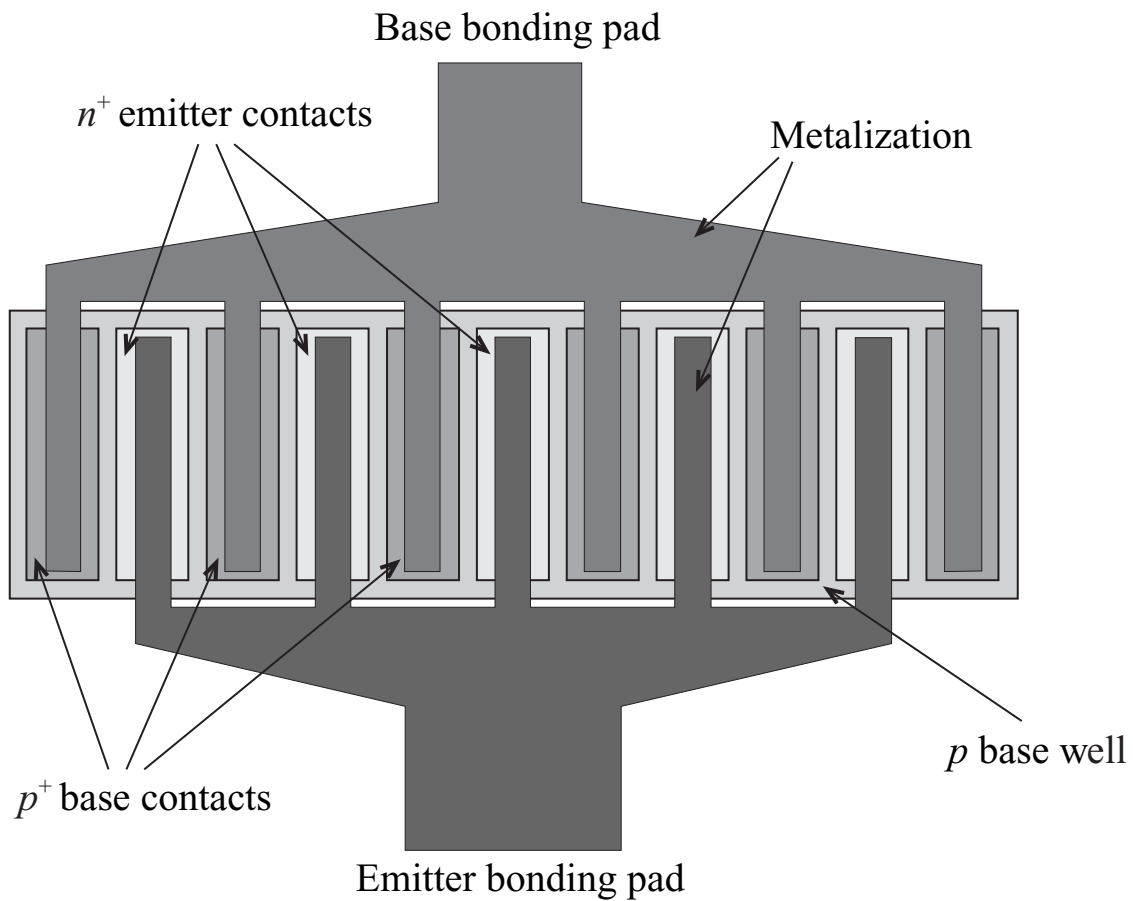
**Figure 6-26** Electric circuit representation of a tunnel diode.



**Figure 6-27** Tunnel diode circuit for amplification/oscillation behavior.

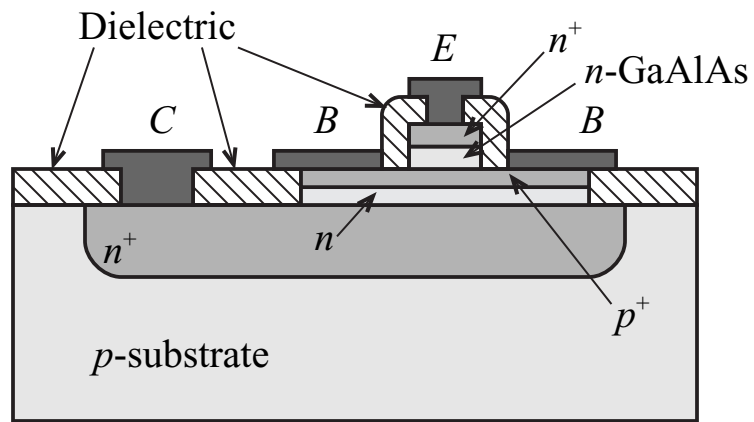


(a) Cross-sectional view of a multifinger bipolar junction transistor

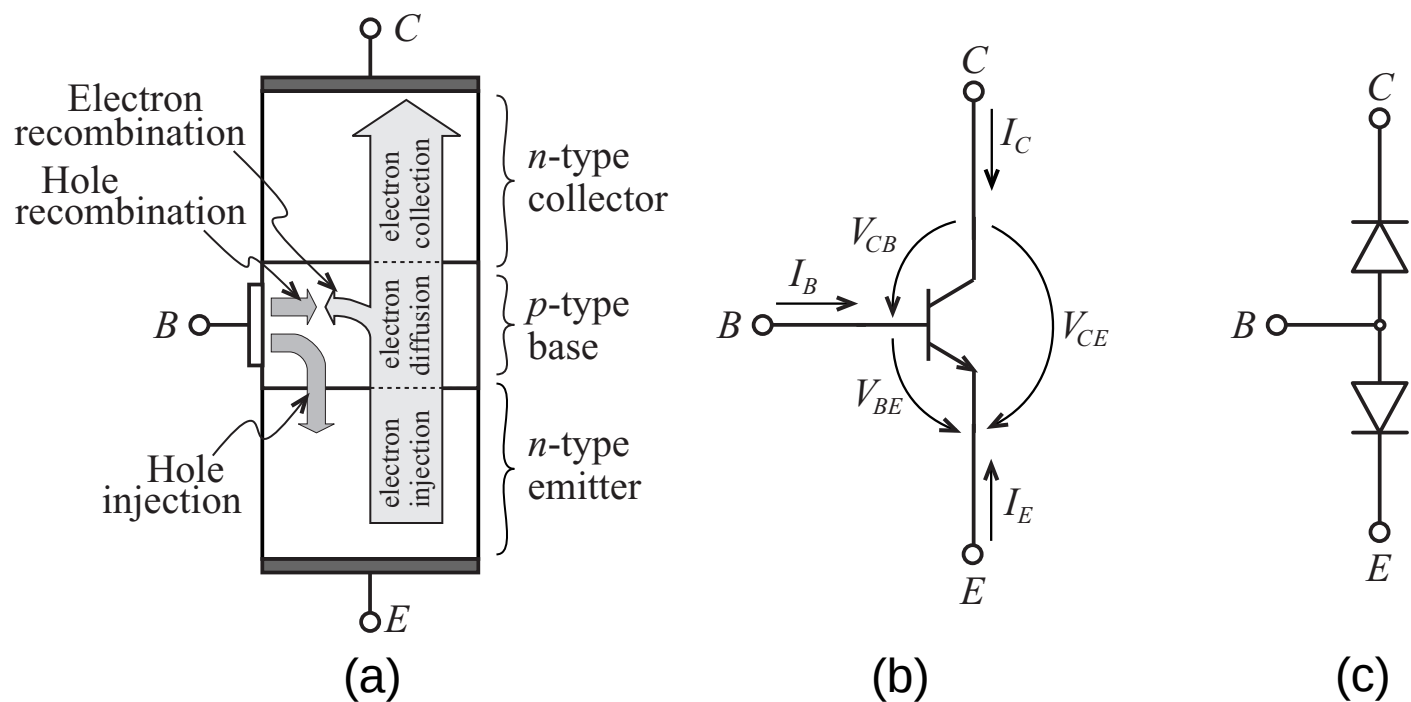


(b) Top view of a multifinger bipolar junction transistor

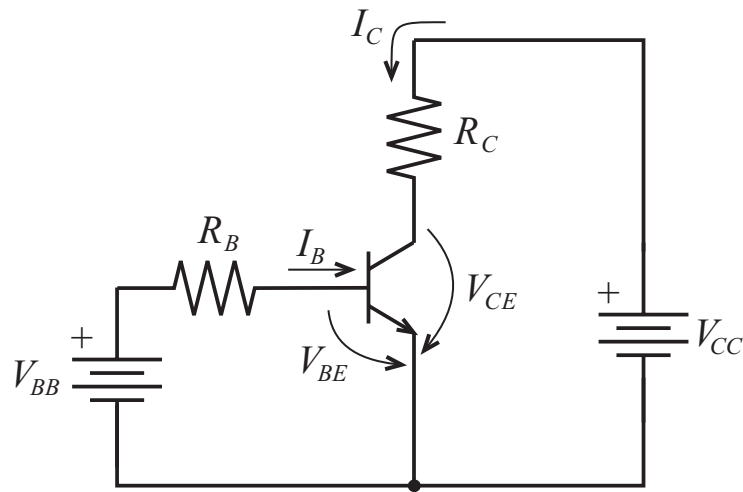
**Figure 6-28** Interdigitated structure of high-frequency BJT.



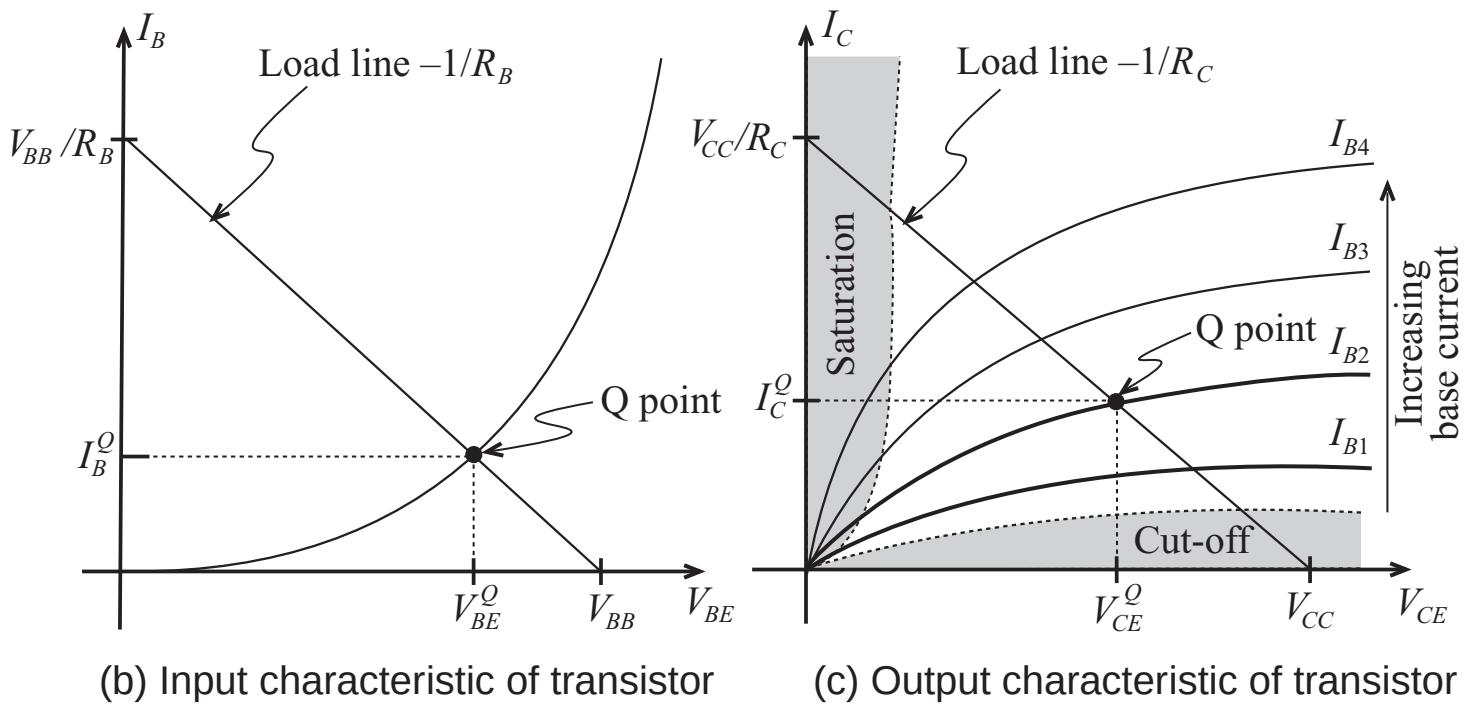
**Figure 6-29** Cross-sectional view of a GaAs heterojunction bipolar transistor involving a GaAlAs-GaAs interface.



**Figure 6-30** *npn* transistor: (a) structure with electrical charge flow under forward active mode of operation, (b) transistor symbol with voltage and current directions, and (c) diode model.



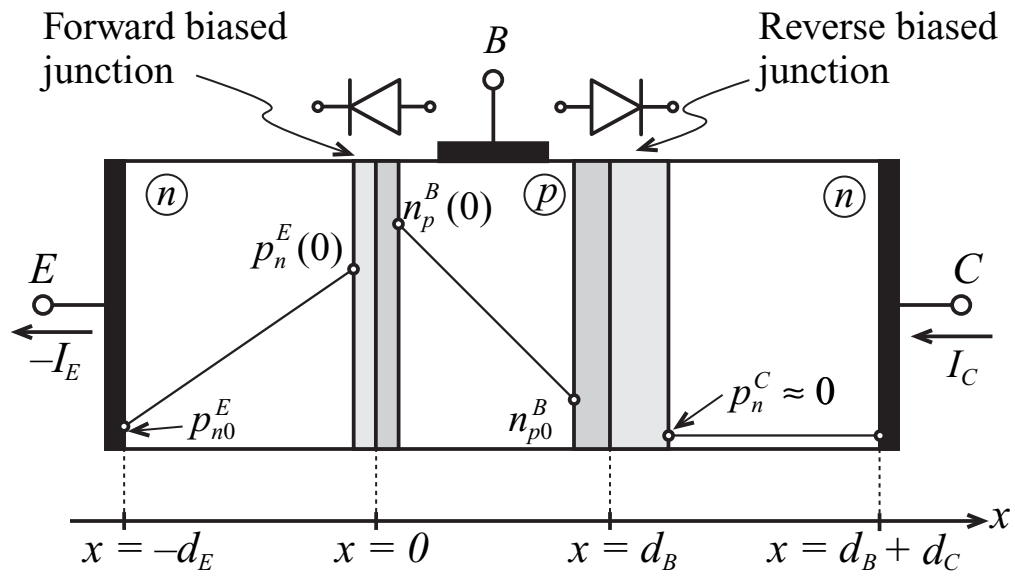
(a) Biasing circuit for *npn* BJT in common-emitter configuration



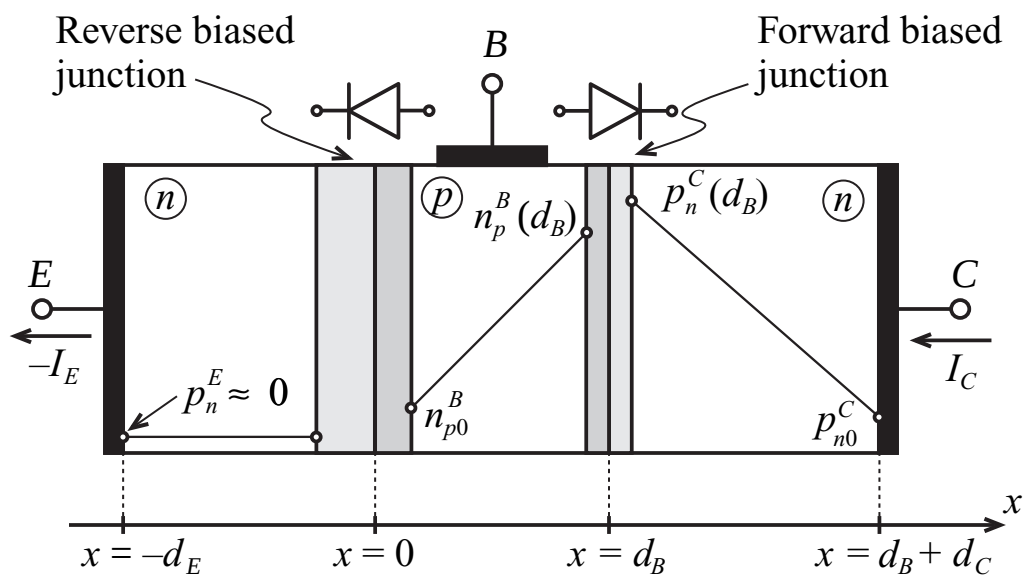
**Figure 6-31** Biasing and input, output characteristics of an *npn* BJT.

**Table 6-3** BJT parameter nomenclature

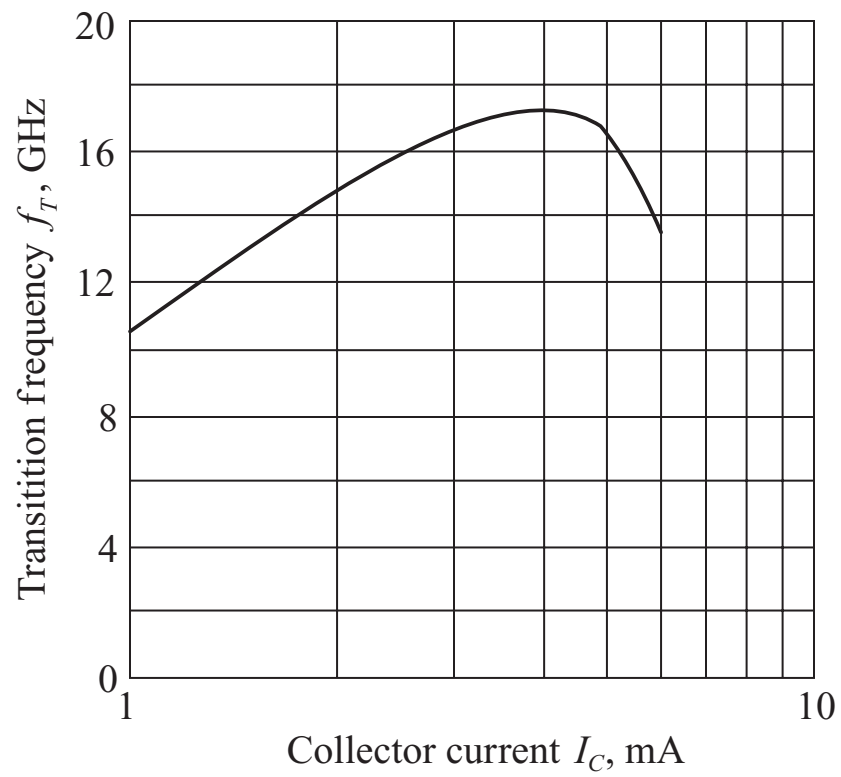
| Parameter description                                 | Emitter ( <i>n</i> -type)   | Base ( <i>p</i> -type)      | Collector ( <i>n</i> -type) |
|-------------------------------------------------------|-----------------------------|-----------------------------|-----------------------------|
| Doping level                                          | $N_D^E$                     | $N_A^B$                     | $N_D^C$                     |
| Minority carrier concentration in thermal equilibrium | $p_{n_0}^E = n_i^2 / N_D^E$ | $n_{p_0}^B = n_i^2 / N_A^B$ | $p_{n_0}^C = n_i^2 / N_D^C$ |
| Majority carrier concentration in thermal equilibrium | $n_{n_0}^E$                 | $p_{p_0}^B$                 | $n_{n_0}^C$                 |
| Spatial extent                                        | $d_E$                       | $d_B$                       | $d_C$                       |



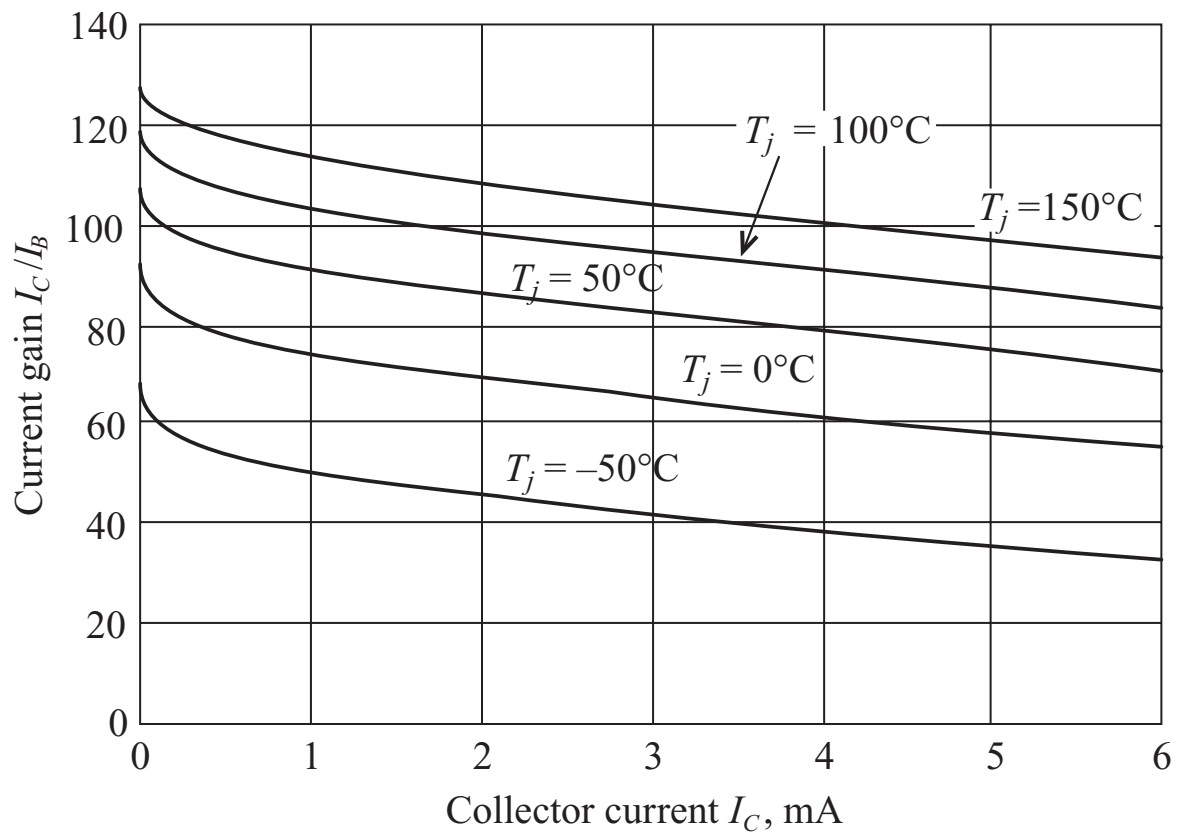
**Figure 6-32** Minority carrier concentrations in forward active BJT.



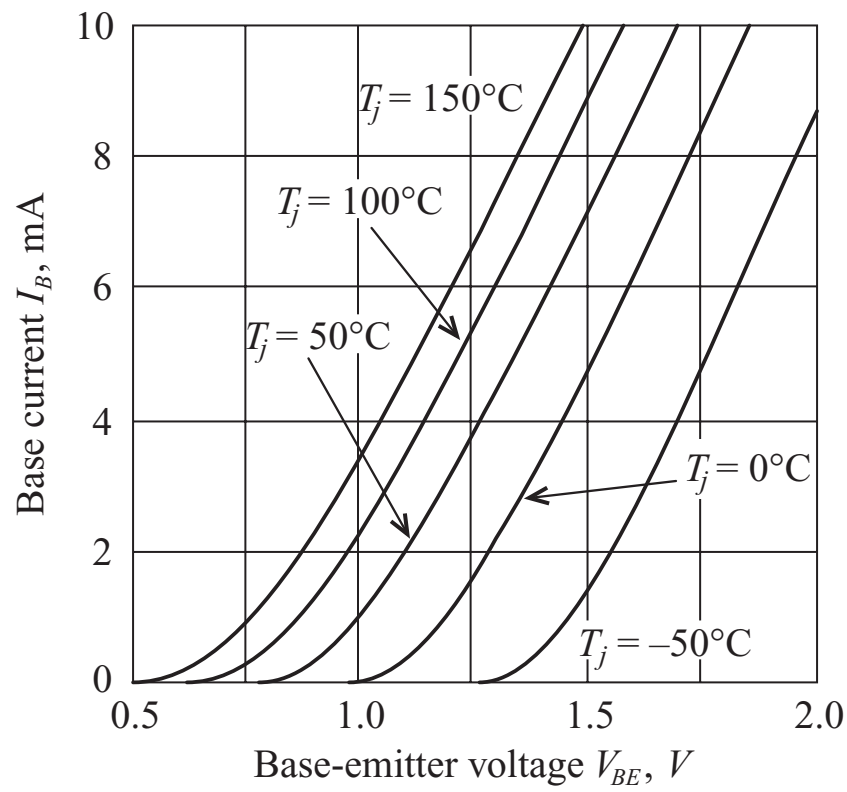
**Figure 6-33** Reverse active mode of BJT.



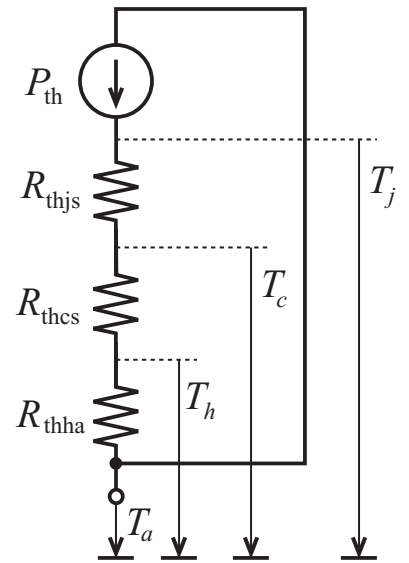
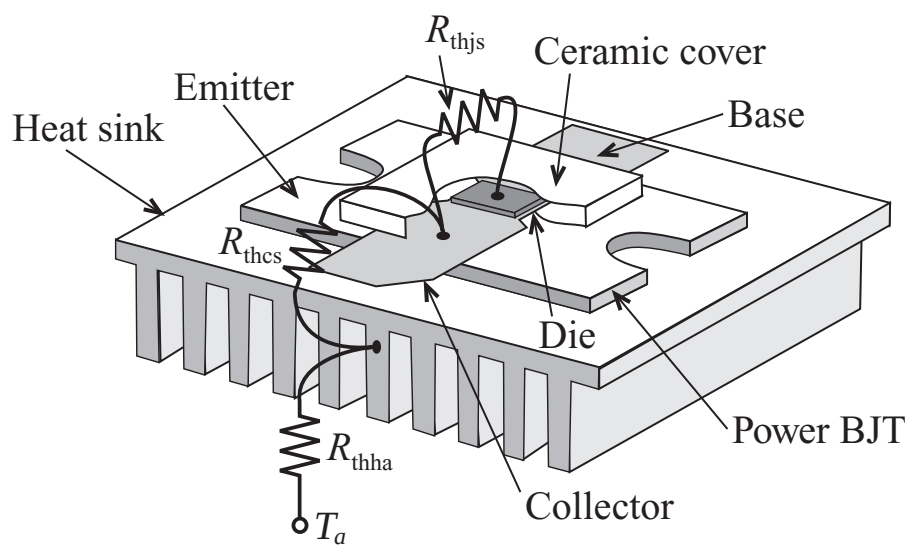
**Figure 6-34** Transition frequency as a function of collector current for the 17 GHz *npn* wideband transistor BFG403W (courtesy of Philips Semiconductors).



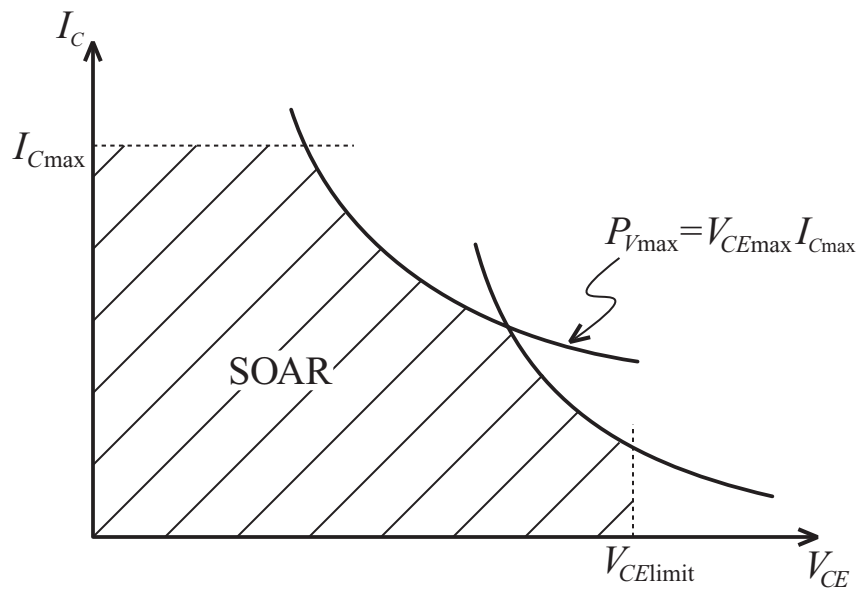
**Figure 6-35** Current gain  $\beta_F = \alpha_F / (1 - \alpha_F)$  as a function of collector current for various junction temperatures at a fixed  $V_{CE}$ .



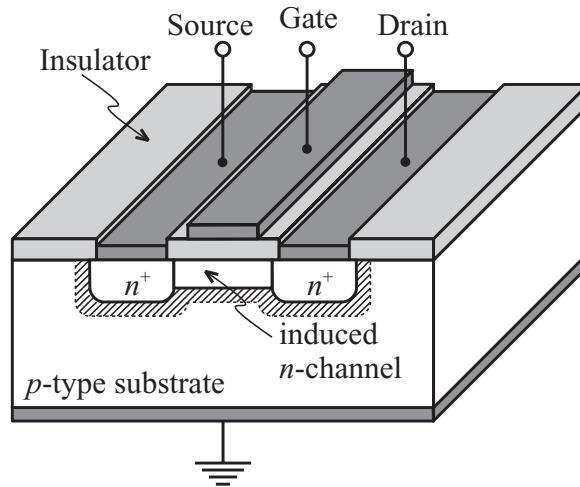
**Figure 6-36** Typical base current as a function of base-emitter voltage for various junction temperatures at a fixed  $V_{CE}$ .



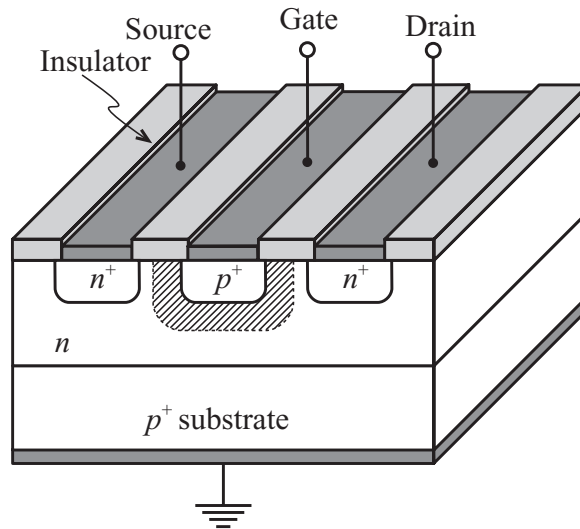
**Figure 6-37** Thermal equivalent circuit of BJT.



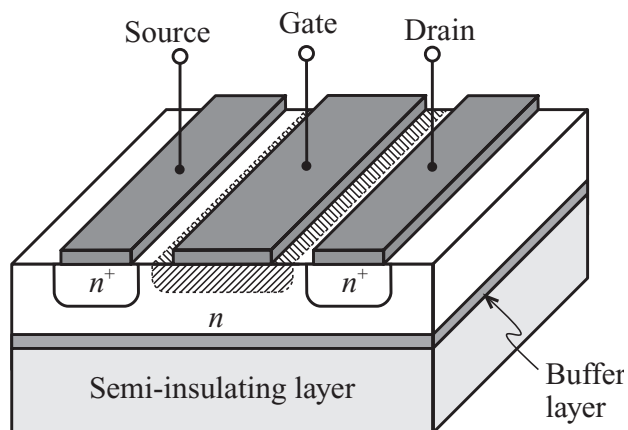
**Figure 6-38** Operating domain of BJT in active mode with breakdown mechanisms.



(a) Metal insulator semiconductor FET (MISFET)

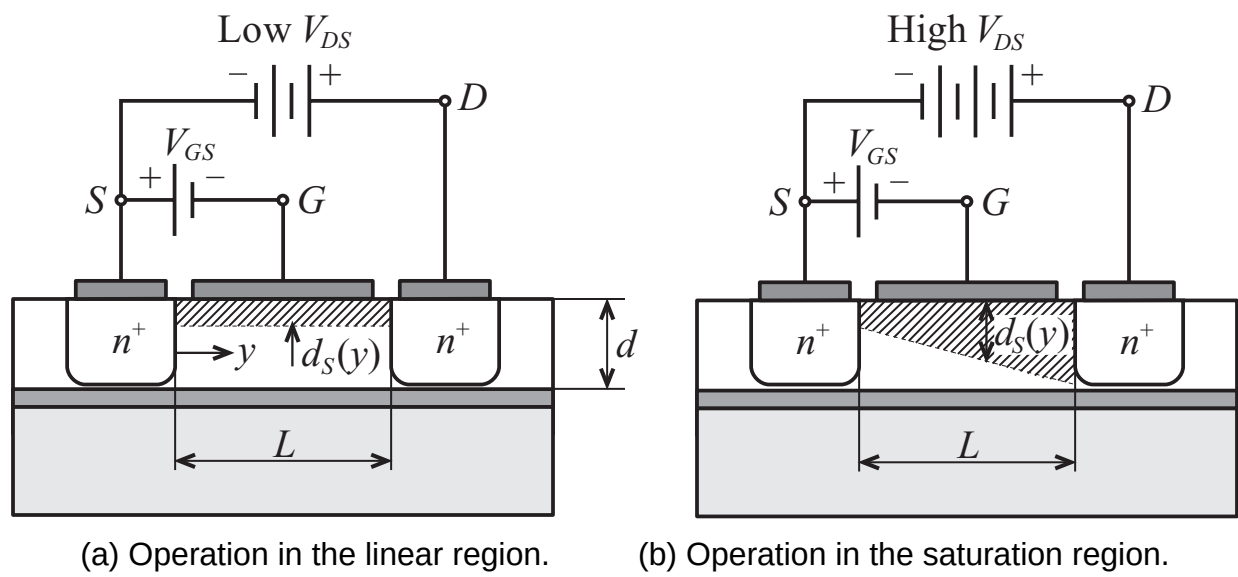


(b) Junction field effect transistor (JFET)

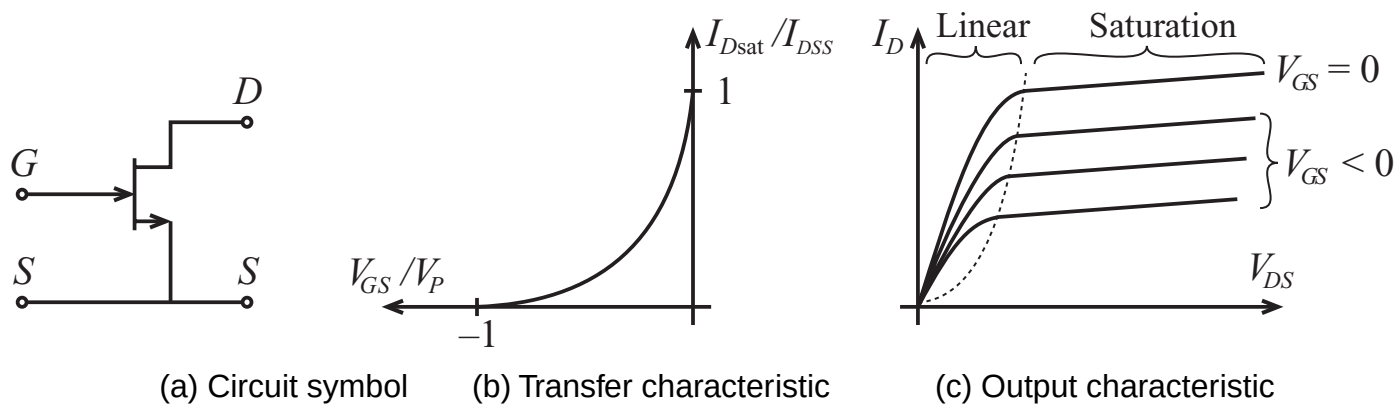


(c) Metal semiconductor FET (MESFET)

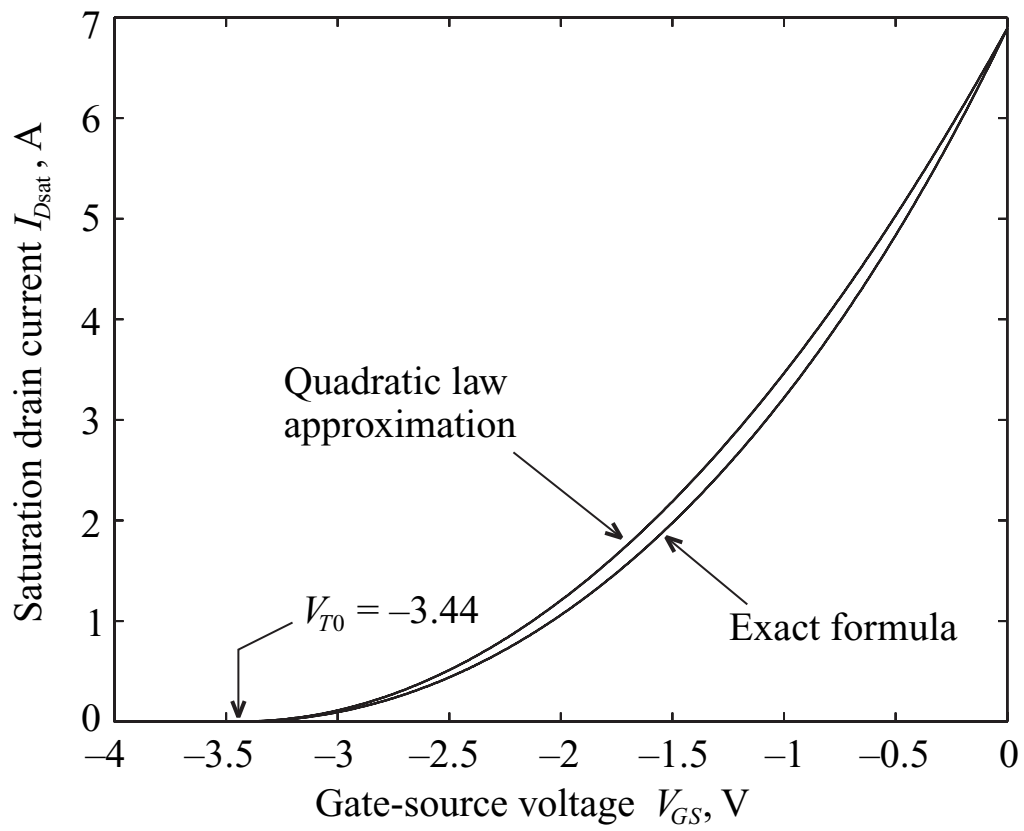
**Figure 6-39** Construction of (a) MISFET, (b) JFET, and (c) MESFET. The shaded areas depict the space charge domains.



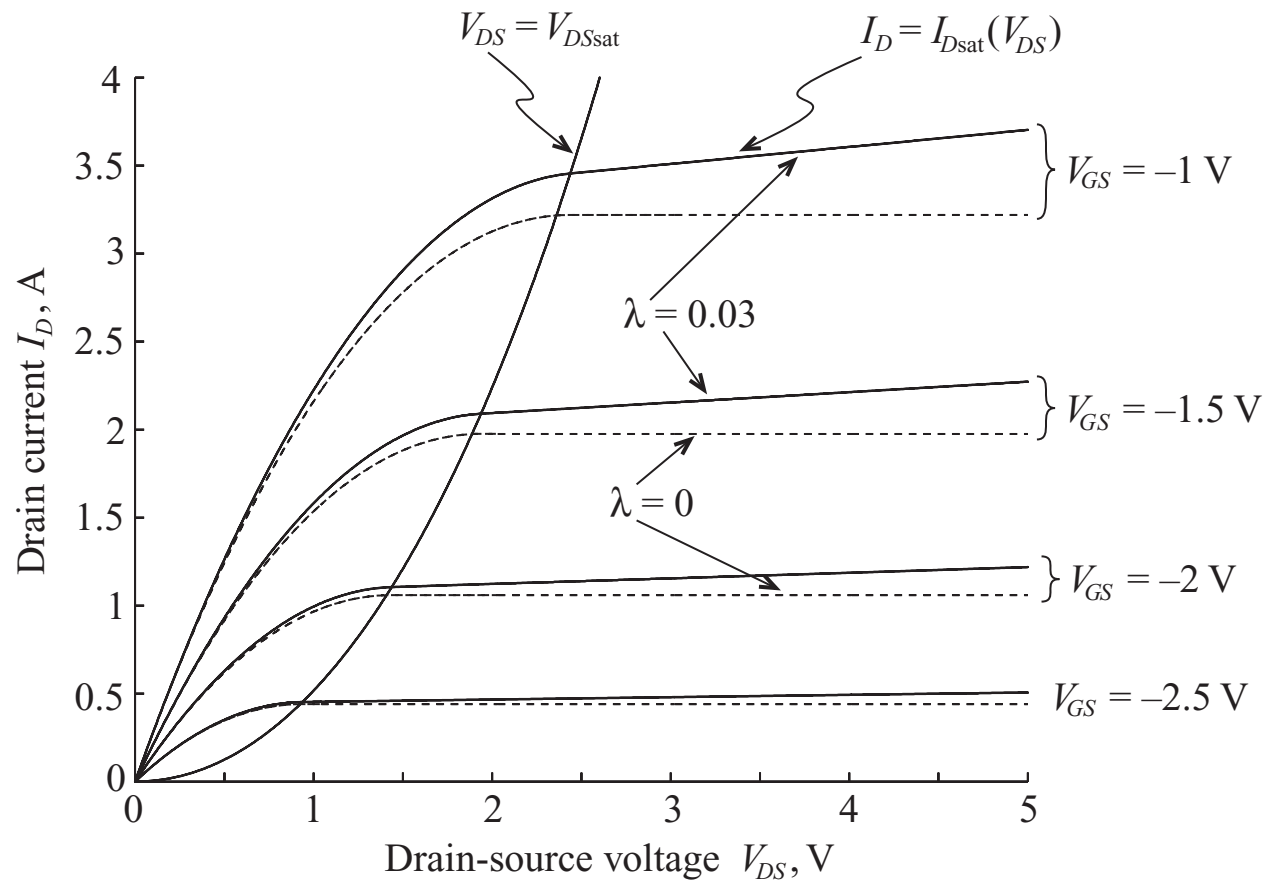
**Figure 6-40** Functionality of MESFET for different drain-source voltages.



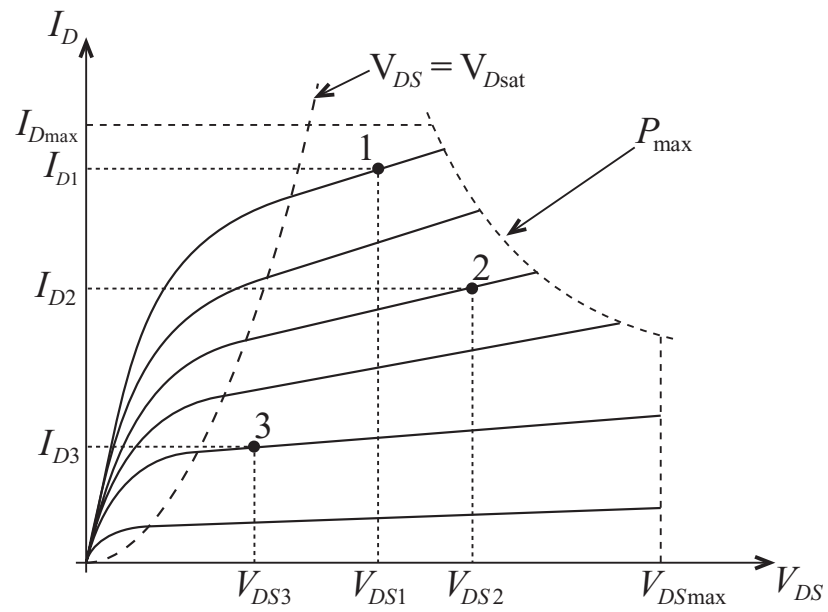
**Figure 6-41** Transfer and output characteristics of an  $n$ -channel MESFET.



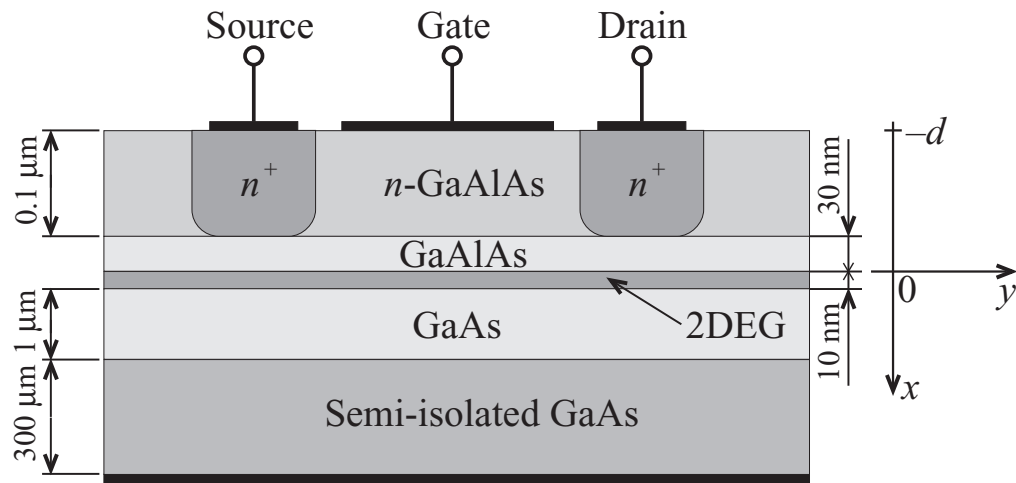
**Figure 6-42** Drain current versus  $V_{GS}$  computed using the exact and the approximate equations (6.87) and (6.88).



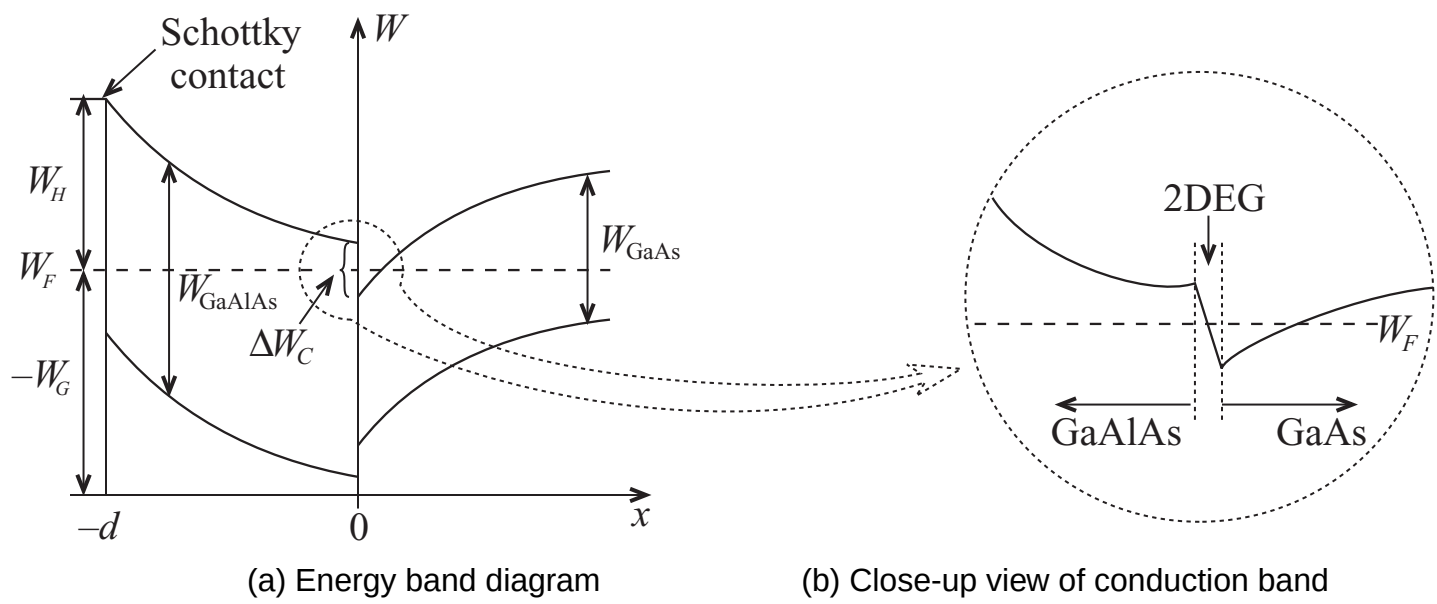
**Figure 6-43** Drain current as a function of applied drain-source voltage for different gate-source biasing conditions.



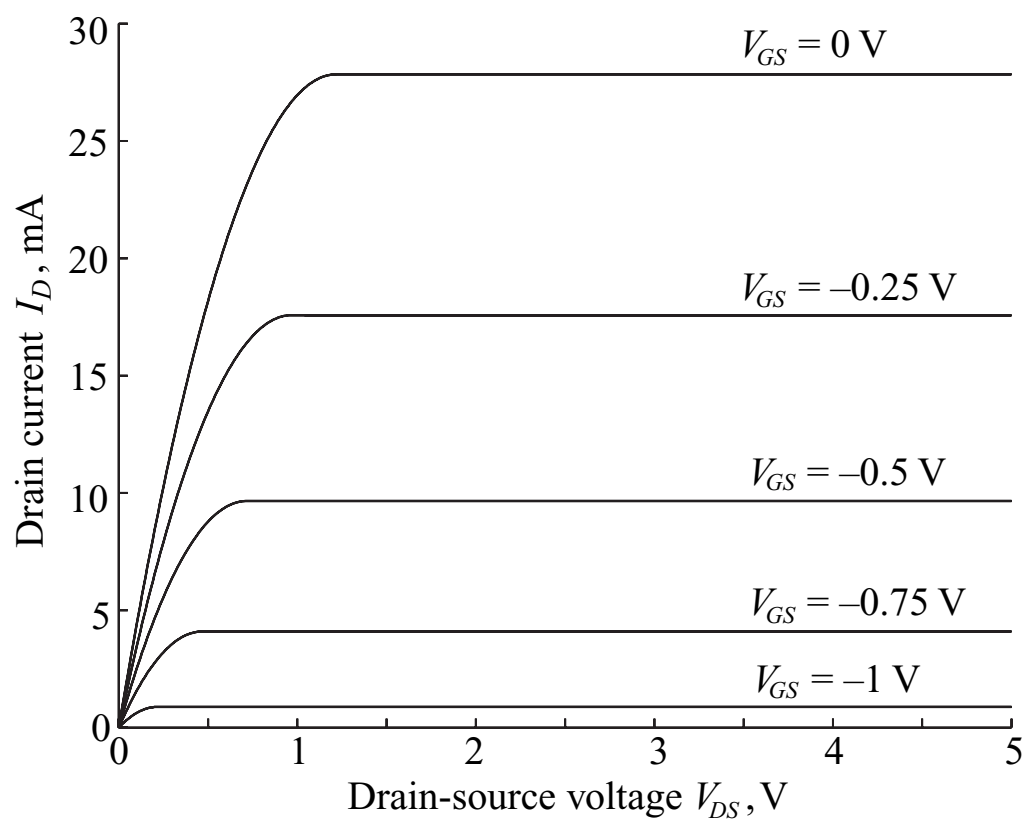
**Figure 6-44** Typical maximum output characteristics and three operating points of MESFET.



**Figure 6-45** Generic heterostructure of a depletion-mode HEMT.



**Figure 6-46** Energy band diagram of GaAlAs-GaAs interface for an HEMT.



**Figure 6-47** Drain current in a GaAs HEMT.