Session 6: Solid State Devices

Transferred Electron Effects

Outline

- A
  - B
  - C
  - D
  - E
- F
  - G
- H
- I
- J

Outline

- Ref: Brennan and Brown
  Sze and Ng, Chapter10

Transferred Electron Effects

k-space transfer	intrinsic property of the semiconductor, and as such cannot be readily engineered
real-space transfer	induced artificially within a semiconductor system and as such can be engineered

K-Space Transfer

1-D continuity equation $$\frac{\partial n}{\partial t} - \frac{1}{q}\frac{\partial J}{\partial x} = 0$$

$$\frac{d\mathcal{E}}{dx} = -\frac{q\delta n}{\epsilon} \qquad \delta n = n - n_0$$

$$J = q\mu_n n\mathcal{E} + qD_n\nabla_x n \qquad \frac{1}{q}\frac{dJ}{dx} = D_n\frac{\partial^2 n}{\partial x^2} + \frac{1}{q\rho}\frac{d\mathcal{E}}{dx}\mathcal{E} \qquad \rho = 1/q\mu_n n$$

$$\frac{1}{q}\frac{dJ}{dx} = D_n\frac{\partial^2 n}{\partial x^2} - \frac{n - n_0}{\rho\epsilon}$$

$$-\frac{dn}{dt} + D_n\frac{d^2 n}{dx^2} - \frac{n - n_0}{\rho\epsilon} = 0$$

$$-\frac{d(n - n_0)}{dt} + D_n\frac{d^2(n - n_0)}{dx^2} - \frac{n - n_0}{\rho\epsilon} = 0$$

$$n - n_0 = u(x)T(t) \qquad \frac{D_n}{u}\frac{d^2 u}{dx^2} - \frac{1}{\rho\epsilon} = \frac{1}{T}\frac{dT}{dt}$$

K-Space Transfer

$$\frac{D_n}{u}\frac{d^2u}{dx^2} - \frac{1}{\rho\epsilon} = \frac{1}{T}\frac{dT}{dt}$$

Steady state $\frac{d}{dx} = 0$

$$D_n \frac{d^2(n-n_0)}{dx^2} = \frac{n-n_0}{\rho\epsilon}$$

$$n - n_0 = A_1 e^{x/L_D} + A_2 e^{-x/L_D}$$

Debye length $L_D = \sqrt{kT\epsilon/q^2 n_0}$

$$n - n_0 = \delta n(0)\, e^{-x/L_D}$$

$$\frac{1}{T}\frac{dT}{dt} = -\frac{1}{\rho\epsilon}$$

$$T = A\, e^{-t/\rho\epsilon}$$

$$\tau = \rho\epsilon = \epsilon/q\mu_n n_0$$

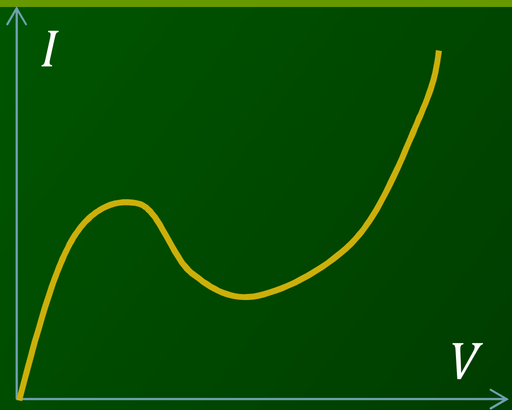
$$n = n_0 + (n - n_0)_{t=0}\, e^{-t/\tau}$$

$$\tau >? < 0$$

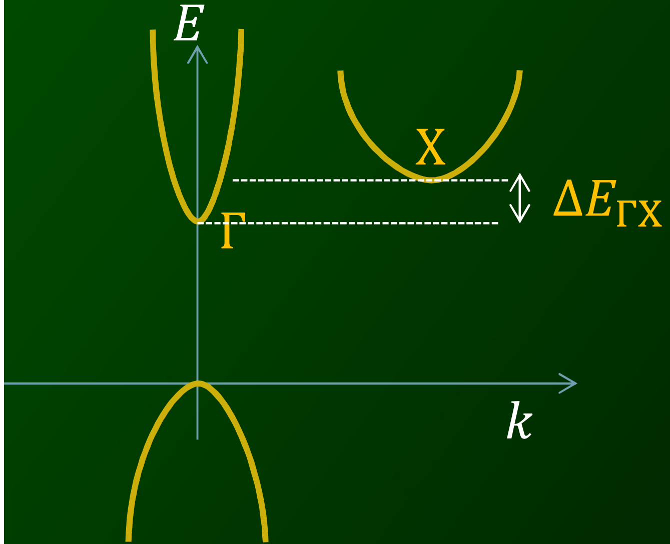
negative differential resistance (NDR)

$$\tau = \rho\epsilon = RC$$

NDR



$$\sigma = q(\mu_\Gamma n_\Gamma + \mu_X n_X)$$



$$\frac{d\sigma}{d\mathcal{E}} = q\left(\mu_\Gamma \frac{dn_\Gamma}{d\mathcal{E}} + \mu_X \frac{dn_X}{d\mathcal{E}}\right) + q\left(n_\Gamma \frac{d\mu_\Gamma}{d\mathcal{E}} + n_X \frac{d\mu_X}{d\mathcal{E}}\right)$$

$$n = n_\Gamma + n_X = cte \qquad \frac{dn_\Gamma}{d\mathcal{E}} = -\frac{dn_X}{d\mathcal{E}}$$

$$\mu_\Gamma \approx \mathcal{E}^p \qquad \mu_X \approx \mathcal{E}^p$$

$$\frac{d\sigma}{d\mathcal{E}} = q(\mu_\Gamma - \mu_X)\frac{dn_\Gamma}{d\mathcal{E}} + q(\mu_\Gamma n_\Gamma + \mu_X n_X)\frac{p}{\mathcal{E}}$$

NDR

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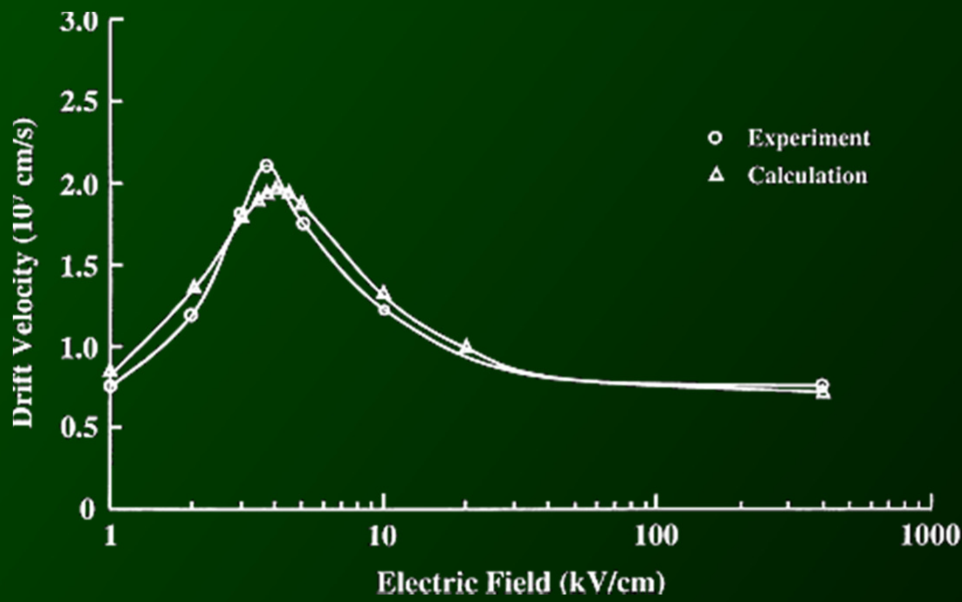
$$\frac{d\sigma}{d\mathcal{E}} = q(\mu_\Gamma - \mu_X)\frac{dn_\Gamma}{d\mathcal{E}} + q(\mu_\Gamma n_\Gamma + \mu_X n_X)\frac{p}{\mathcal{E}}$$

$$J = \sigma\mathcal{E} \qquad \frac{dJ}{d\mathcal{E}} = \sigma + \mathcal{E}\frac{d\sigma}{d\mathcal{E}} \qquad \frac{dJ}{d\mathcal{E}} < 0 \qquad -\frac{d\sigma/d\mathcal{E}}{\sigma/\mathcal{E}} > 1$$

$$\left[\frac{\mu_\Gamma - \mu_X}{\mu_\Gamma + (n_X/n_\Gamma)\mu_X}\left(-\frac{\mathcal{E}}{n_\Gamma}\frac{dn_\Gamma}{d\mathcal{E}}\right) - p\right] > 1$$



$$\frac{n_\Gamma}{n_X} = \frac{N_\Gamma}{N_X}\, e^{-\Delta E_{\Gamma X}/kT}$$

$$= \left(\frac{m_\Gamma}{m_X}\right)^{3/2} e^{-\Delta E_{\Gamma X}/kT}$$

Real-Space Transfer

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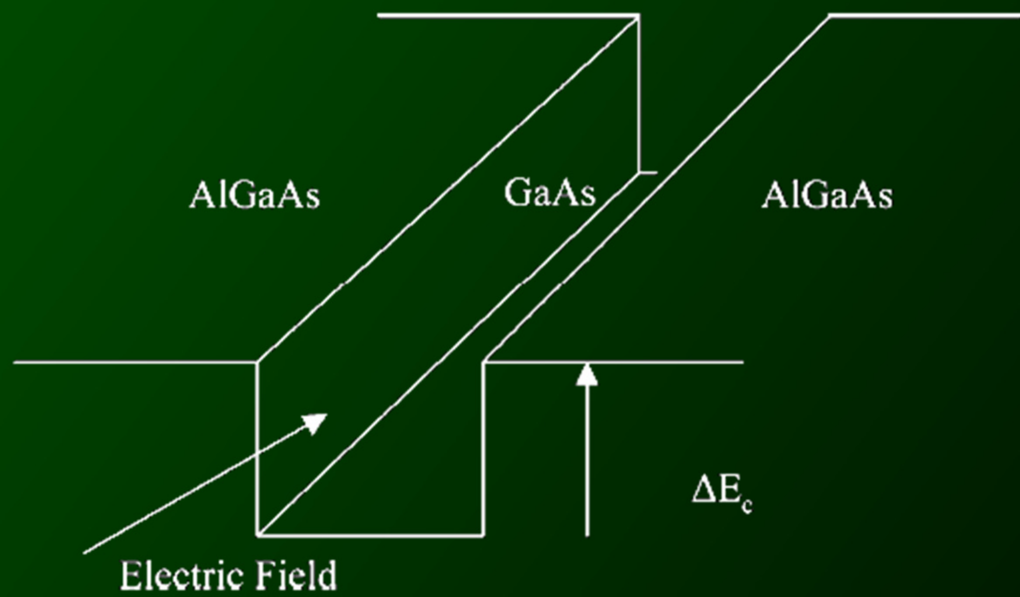


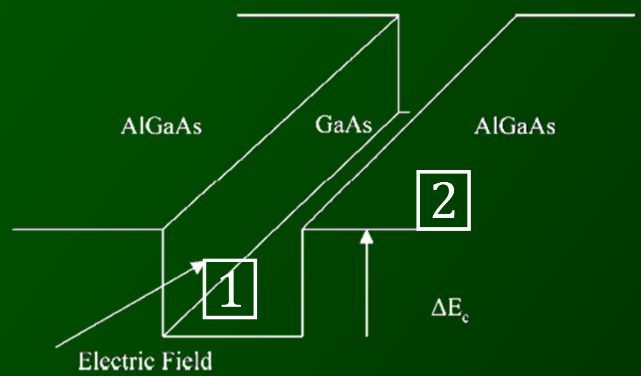
$GaAs$ $\mu \propto 1/m^*$

$Al_xGa_{1-x}As$ $x < 45\%$ direct : Γ valley $m^*_{AlGaAs} > m^*_{GaAs}$

$x > 45\%$ indirect : X valley

√ NDR can occur

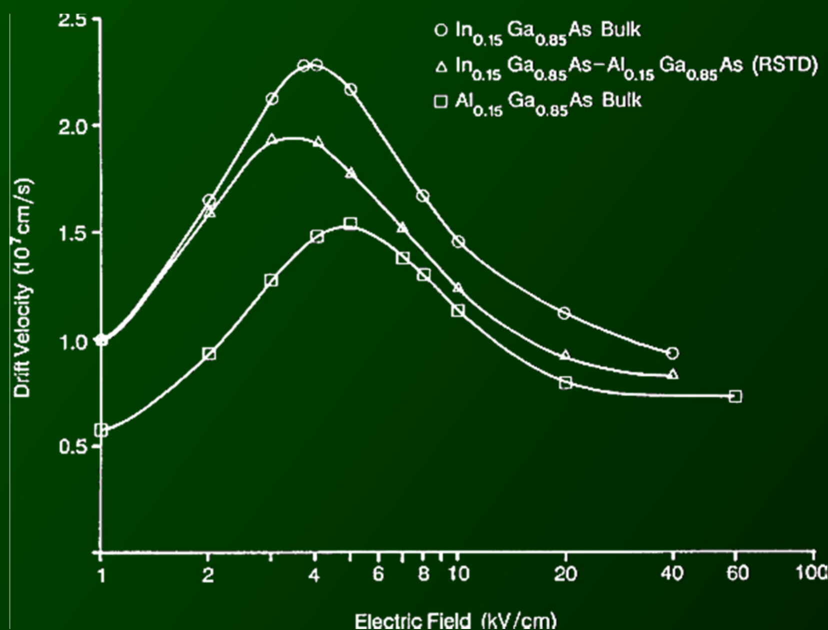
Real-Space Transfer

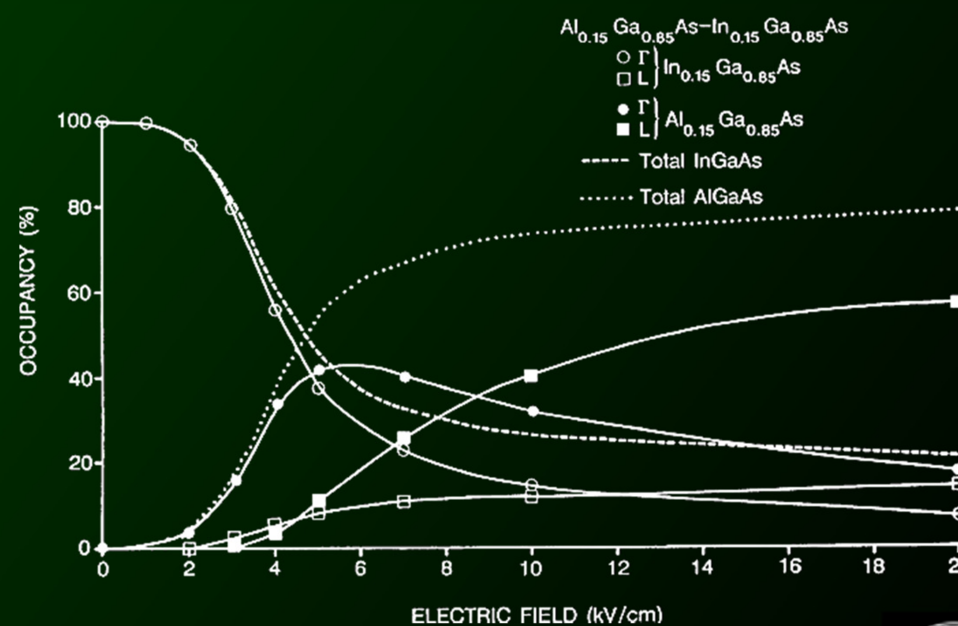


$$\bar{v} = \frac{v_1 n_1 + v_2 n_2}{n_1 + n_2}$$

$$n = \int D(E) f(E) dE$$

$$\frac{n_2}{n_1} = \left(\frac{m_2}{m_1}\right)^{3/2} e^{-\Delta E_C / kT_e}$$





Consequences of NDR

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Gunn (1963) observed experimentally microwave oscillations in bulk GaAs under the application of a bias

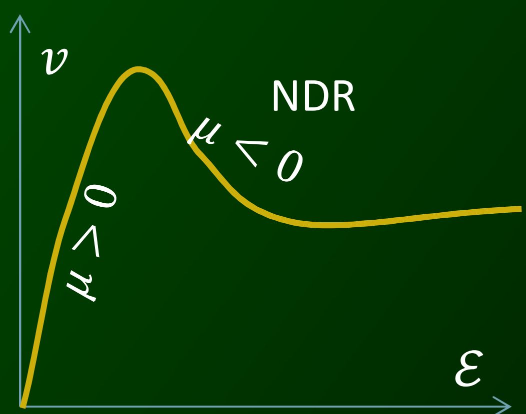
assume that diffusion can be neglected $J = qn\mu\mathcal{E}$ $\qquad \frac{\partial n}{\partial t} - \frac{1}{q}\frac{\partial J}{\partial x} = 0$

$$\frac{dn}{dt} = \frac{d}{dx}(n\mu\mathcal{E}) = \mathcal{E}\frac{d}{dx}(n\mu) + n\mu\frac{d\mathcal{E}}{dx}$$
$$= \mathcal{E}\frac{d}{dx}(n\mu) - qn\mu\frac{n-n_0}{\epsilon}$$
$$= \mathcal{E}\frac{d}{dx}(n\mu) - \frac{n-n_0}{\tau}$$

$$n - n_0 = u(x)T(t)$$
$$n = (n-n_0)e^{-t/\tau} + n_0$$

negative τ $\quad n = (n-n_0)e^{t/\tau} + n_0$

$$\mu = v/\mathcal{E}$$



$$t_{tr} = \frac{L}{v_D} > \tau = \frac{\epsilon}{qn\mu} \quad \rightarrow LN_D > \frac{\epsilon v_D}{q\mu} \sim 10^{12} cm^{-2}$$

for GaAs

Gunn Diode
Transferred Electron-Effect Oscillators

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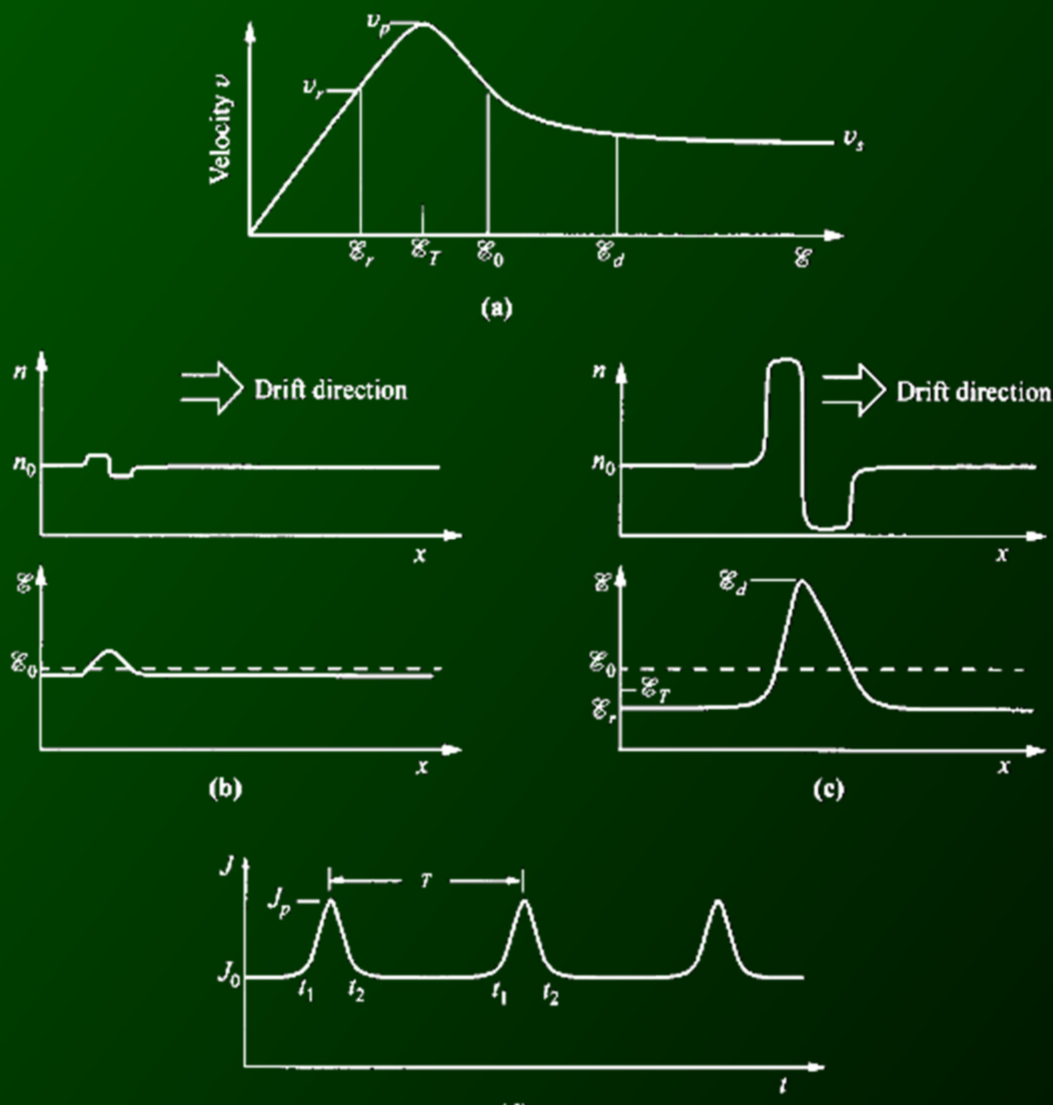

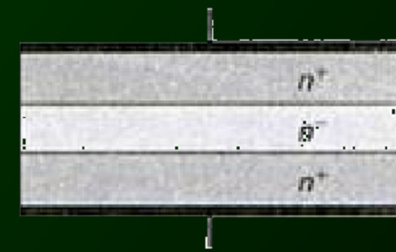

Functional Devices

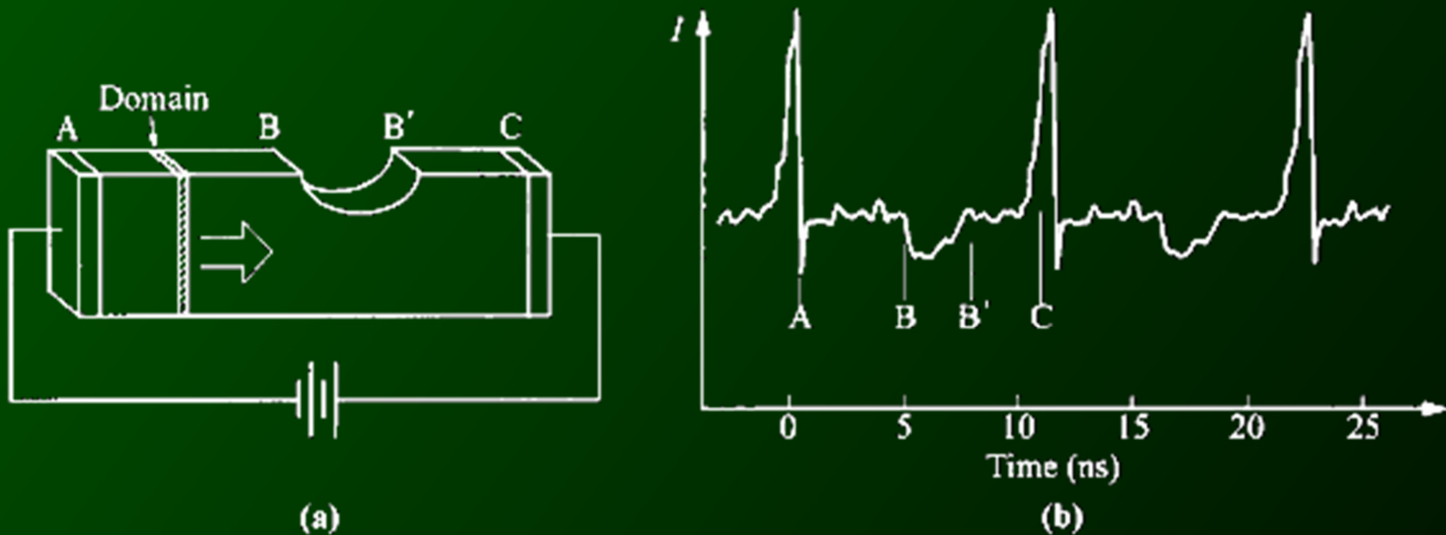

Fig. 18 (a) A TED with nonuniform cross-section and (b) its current waveform. Labels in (b) correspond to the location of domain at the specific time. (After Ref. 47.)

limited space-charge accumulation (LSA) mode

Negative Differential Resistance Transistor

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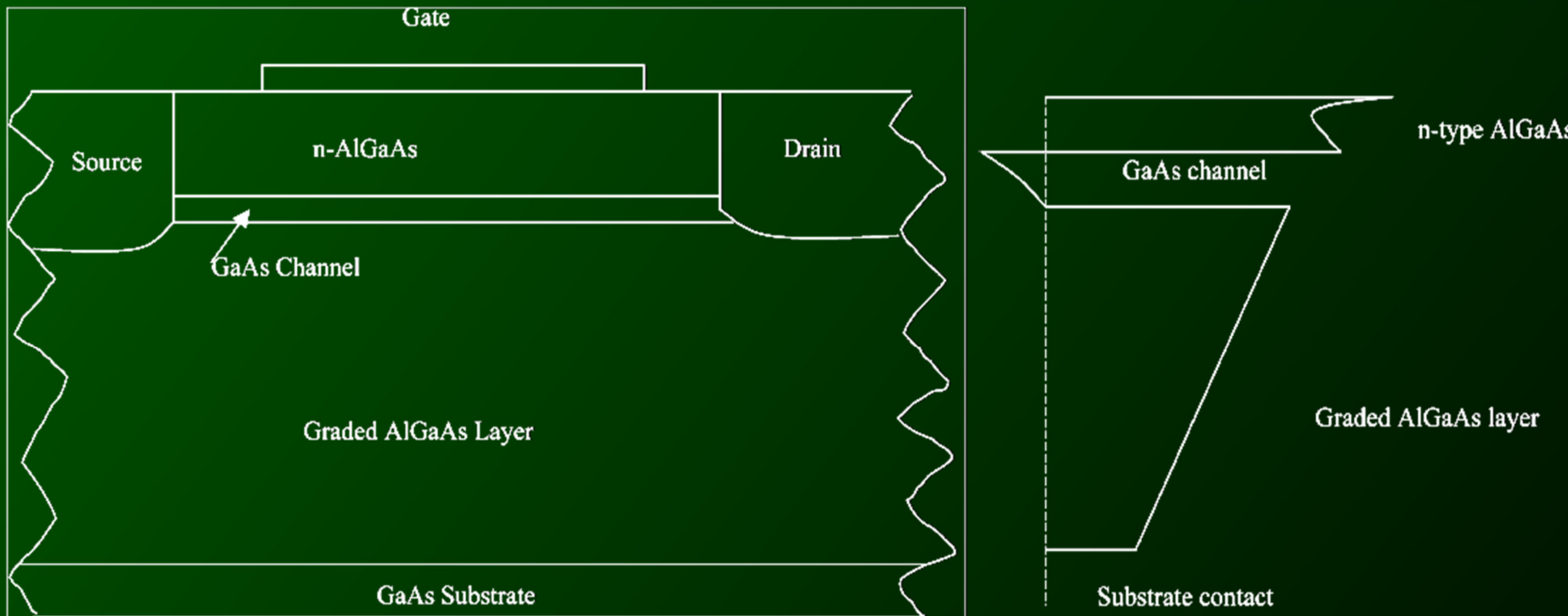
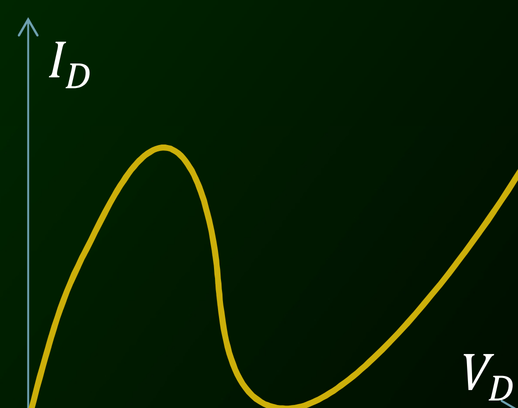


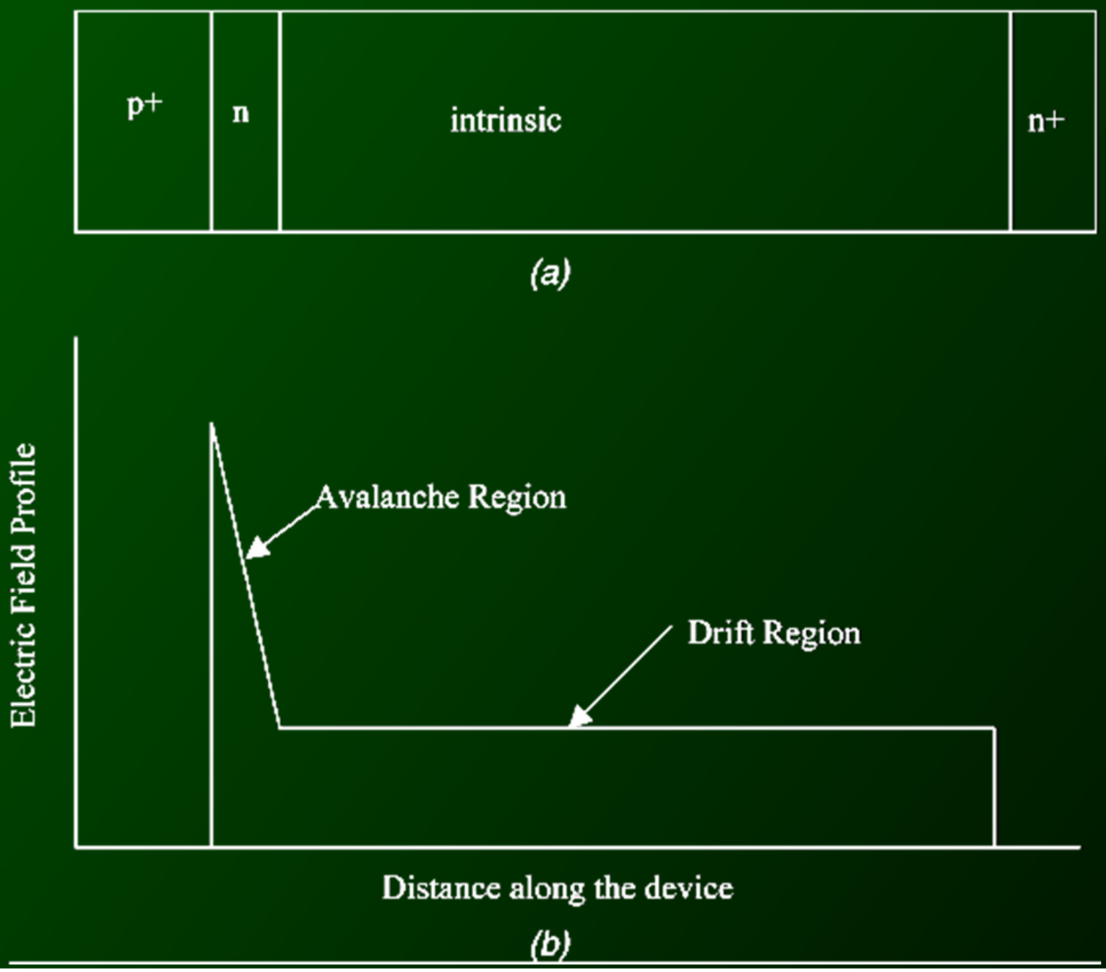
FIGURE 5.6.1 Real-space transfer field-effect transistor (NERFET).



IMPATT Diode

IMPATT diode is not generally a transferred electron device

Within the IMPATT NDR is induced by driving the current and voltage out of phase with one another



avalanche and transit time regions must be designed such that the current and voltage are driven out of phase

(1) the finite rise and decay time of the avalanche current
(2) the finite transit time of the carriers through the drift region

HBT