IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2017

EEE PART II: MEng, BEng and ACGI

**Corrected copy**

**DEVICES**

Monday, 19 June 10:00 am

Time allowed: 1:30 hours

**There are TWO questions on this paper.**

**Answer ALL questions. Question One carries 25 marks and Question Two carries 25 marks.**

**Any special instructions for invigilators and information for candidates are on page 1.**

Examiners responsible First Marker(s) : K. Fobelets
Second Marker(s) : W.T. Pike

**Special instructions for invigilators**

**Special instructions for students**

*Do not use red nor green ink.*

*Do not use pencil.*

**Constants**

| | |
|---|---|
| permittivity of free space: | $\varepsilon_o = 8.85 \times 10^{-12}$ F/m |
| permeability of free space: | $\mu_o = 4\pi \times 10^{-7}$ H/m |
| intrinsic carrier concentration in Si: | $n_i = 1.45 \times 10^{10}$ cm$^{-3}$ at $T = 300$ K |
| dielectric constant of Si: | $\varepsilon_{Si} = 11$ |
| dielectric constant of $SiO_2$: | $\varepsilon_{ox} = 4$ |
| thermal voltage: | $V_T = kT/e = 0.026$ V at $T = 300$ K |
| charge of an electron: | $e = 1.6 \times 10^{-19}$ C |
| Planck's constant: | $h = 6.63 \times 10^{-34}$ Js |
| bandgap of Si: | $E_G = 1.12$ eV at $T = 300$ K |
| electron affinity of Si | $\chi = 4.05$ eV at $T = 300$ K |
| effective density of states of Si: | $N_C = 3.2 \times 10^{19}$ cm$^{-3}$ at $T = 300$ K<br>$N_V = 1.8 \times 10^{19}$ cm$^{-3}$ at $T = 300$ K |

**Formulae**

$$\left.\begin{aligned} J_n(x) &= e\mu_n n(x)E(x) + eD_n \frac{dn(x)}{dx} \\ J_p(x) &= e\mu_p p(x)E(x) - eD_p \frac{dp(x)}{dx} \end{aligned}\right\}$$

Drift-diffusion current equations

$$\left.\begin{aligned} \frac{\partial \delta n}{\partial t} &= D_n \frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{\tau_n} \\ \frac{\partial \delta p}{\partial t} &= D_p \frac{\partial^2 \delta p}{\partial x^2} - \frac{\delta p}{\tau_p} \end{aligned}\right\}$$

Continuity equations of minority carriers

$$\left.\begin{aligned} J_n &= \frac{eD_n n_p}{L_n}\left(e^{\frac{eV}{kT}} - 1\right) \\ J_p &= \frac{eD_p p_n}{L_p}\left(e^{\frac{eV}{kT}} - 1\right) \end{aligned}\right\}$$

Text-book diode diffusion currents

$$V_0 = \frac{kT}{e}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Built-in voltage

$$c = c_0 \exp\left(\frac{eV}{kT}\right) \text{ with } \begin{cases} c = p_n \text{ or } n_p \\ c_0 \text{ bulk minority carrier concentration} \end{cases}$$

Minority carrier injection under bias $V$

$$\delta c = \Delta c \exp\left(\frac{-x}{L}\right) \text{ with } \begin{cases} \delta c = \delta p_n \text{ or } \delta n_p \\ \Delta c \text{ the excess carrier concentration} \\ \text{at the edge of the depletion region} \end{cases}$$

Excess carrier concentration as a function of distance when recombination occurs – long layer approximation.

$$L = \sqrt{D\tau}$$

Diffusion length

$$D = \frac{kT}{e}\mu$$

Einstein relation

$$C_{diff} = \frac{e}{kT} I\tau$$

Diffusion capacitance

$$i(t) = \frac{Q(t)}{\tau} + \frac{dQ(t)}{dt}$$

Time variation of current and charge

$$\frac{dE}{dx} = \frac{\rho(x)}{\varepsilon}$$

Poisson equation in 1 dimension

$$n = N_C \, exp\left(\frac{E_F - E_C}{kT}\right)$$

$$p = N_V \, exp\left(\frac{E_V - E_F}{kT}\right)$$

Carrier concentrations

1. Influence of temperature on pn diode characteristics

a) Derive the expression of the intrinsic carrier concentration, $n_i$ as a function of the bandgap, $E_G$ and the density of states in the conduction and valence band, $N_c$ and $N_v$. [5]

b) Derive the expression for the built-in voltage, $V_0$ in a pn diode in terms of work functions. Draw the energy band diagram to define the relevant parameters. [5]

c) The current-voltage characteristic of a pn diode measured at different temperatures is given in Fig. 1.1. Explain why the on-voltage shifts to lower voltages with increasing temperature. Where necessary, use equations and graphs to illustrate your answer. The variation of the bandgap and effective density of state is negligible in the given temperature range. [7]

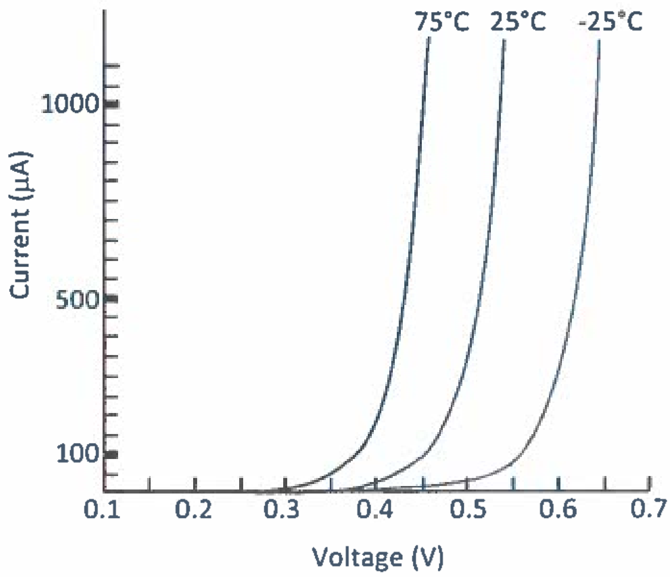


*Figure 1.1: Current-voltage characteristics of a pn diode at different temperatures*

d) The diode whose characteristics are given in Fig. 1.1, is switched from forward to reverse bias. In forward bias, a control circuit maintains a constant voltage drop across the diode of 0.45 V. The amplitude of the reverse bias switching current is controlled at 200 µA. Calculate the increase/decrease of the reverse recovery time when the diode temperature increases from 25 °C to 75 °C. The minority carrier Schottky-Read-Hall lifetime is 1 µs, constant in the given temperature range. Justify any assumptions you make. [8]

2. The insulated-gate bipolar transistor.

a) Draw the material cross section of an insulated-gate bipolar transistor, IGBT. Define the doping types and contacts for your device when the IGBT has a p-type bulk contact layer. Make your drawing sufficiently large to show the details of the structure clearly. [8]

b) Add the equivalent circuit of the IGBT to the drawing in a), including the parasitic resistances and BJT. Name and define the circuit components. [8]

c) Sketch one output characteristics of the IGBT when it is on. Briefly explain the saturation point. [4]

d) For a typical transient characteristic of an IGBT given in Fig. 2.1, answer the following questions:

i) What causes the delay $t_{dn}$ at switch on? [2]

ii) What causes the delay $t_{f2}$ at switch off? [2]

iii) In the EE2-10A module no overshoots where reported. Explain the possible cause of the overshoot indicated with the circle? [1]

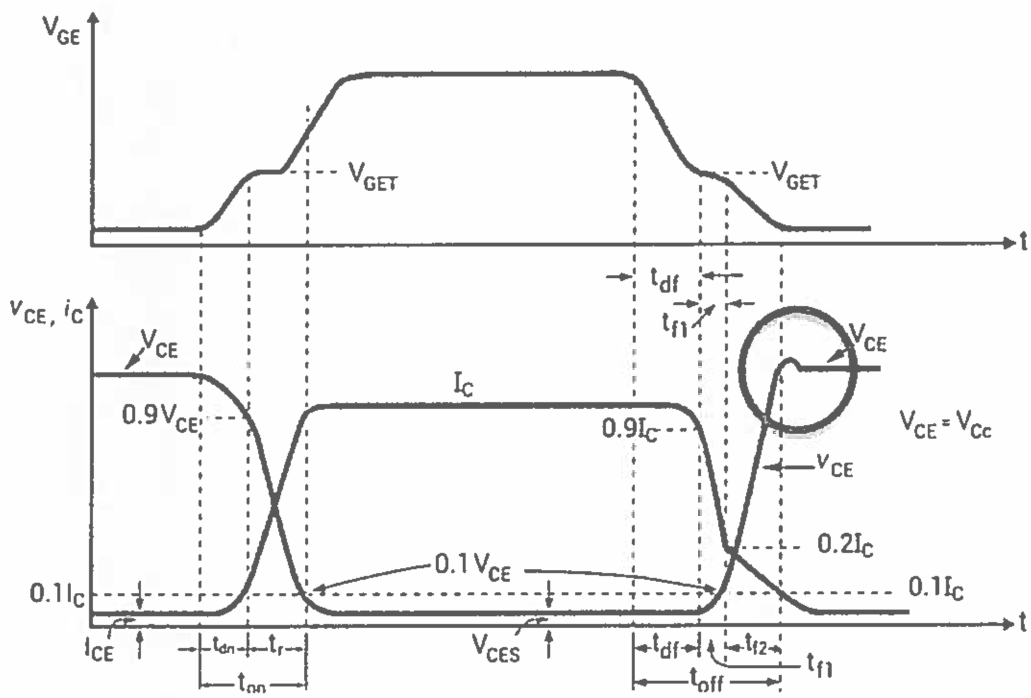


Figure 2.1: Transient characteristics of the IGBT. The symbol $V_{GE}$ denotes the control voltage, $V_{CE}$ the output voltage across the IGBT and $i_C$ the output current.