IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2016

EEE PART II: MEng, BEng and ACGI

Corrected copy

DEVICES

Monday, 6 June 2:00 pm

Time allowed: 1:30 hours

There are TWO questions on this paper.

Answer ALL questions. Question One carries 30 marks and Question Two carries 20 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.

Constants and Formulae

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

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

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

$$\delta c_B = C_1 \exp\left(\frac{x}{L_B}\right) + C_2 \exp\left(\frac{-x}{L_B}\right)$$

$$C_1 = \frac{c_B(W_B) - c_{B_0} - \left(c_B(0) - c_{B_0}\right)\exp\left(\frac{-W_B}{L_B}\right)}{2\sinh\left(\frac{W_B}{L_B}\right)}$$

$$C_2 = \frac{\left(c_B(0) - c_{B_0}\right)\exp\left(\frac{-W_B}{L_B}\right) - \left(c_B(W_B) - c_{B_0}\right)}{2\sinh\left(\frac{W_B}{L_B}\right)}$$

Excess minority carrier concentration in the base of a BJT

C_1, C_2: integration constants
EB junction is at $x = 0$
BC junction is at $x = W_B$
c_{B0}: equilibrium concentration
L_B: minority carrier diffusion length in base

$$w_n = \sqrt{\frac{2\varepsilon}{e} \frac{N_A}{N_A N_D + N_D^2} (V_0 - V)}$$

$$w_p = \sqrt{\frac{2\varepsilon}{e} \frac{N_D}{N_A N_D + N_A^2} (V_0 - V)}$$

$$W_{depl} = \sqrt{\frac{2\varepsilon}{e} \frac{N_A + N_D}{N_A N_D} (V_0 - V)}$$

Depletion regions in pn diode

1.

a) What is the most important recombination process in silicon under relatively low bias conditions? Illustrate/explain your answer with a suitable diagram. [5]

b) Impact ionisation is one of the main carrier generation mechanisms at high voltage levels.

i) Explain and illustrate the concept of impact ionisation using a suitable diagram. [5]

ii) Explain the approach used in high power diodes to lower the probability of impact ionisation. Illustrate your explanation with a diagram if desired. [5]

c) An n$^+$p diode with area $A = 1$ cm^2, $N_D = 5 \times 10^{19}$ cm^{-3} and $N_A = 10^{16}$ cm^{-3}, is switched using the circuit in Fig. 1.1(a). Fig. 1.1(b) gives the result of this experiment. [10]

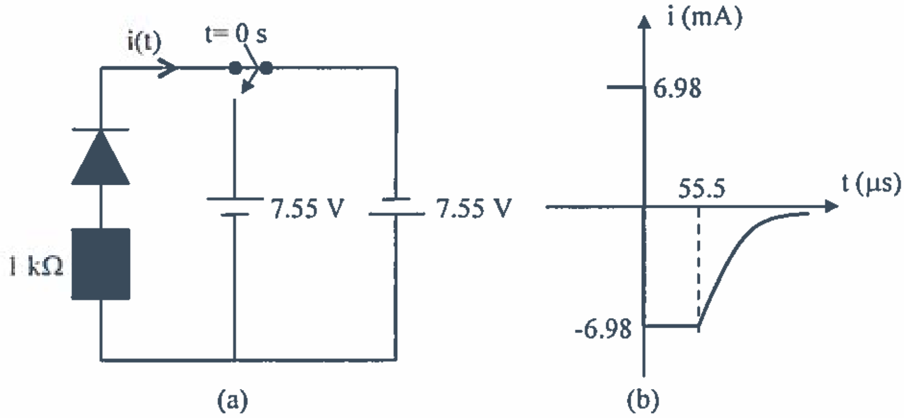

Figure 1.1: (a) the switching circuit, (b) the variation of the current as a function of time for the set-up given in (a).

Derive the electron carrier lifetime, τ_n and diffusion length, L_n for the n$^+$p diode of Fig. 1.1.

d) The output current, $i_c(t)$ of a Si BJT that is switched off at $t = 0$ s by applying a reverse bias voltage across the emitter-base junction, is given in Fig. 1.2. Explain the shape of the graph in Fig. 1.2 using appropriate charge distributions in the BJT. [5]

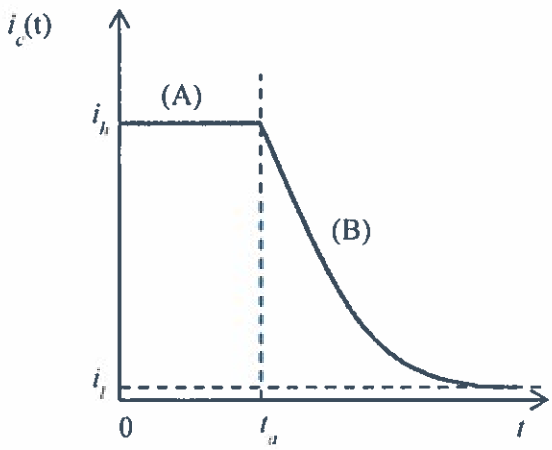

Figure 1.2: The output current $i_c(t)$ of a BJT that is switched from on to off at time $t = 0$ s. (A) is the constant current region. (B) is the exponentially varying current region.

2.

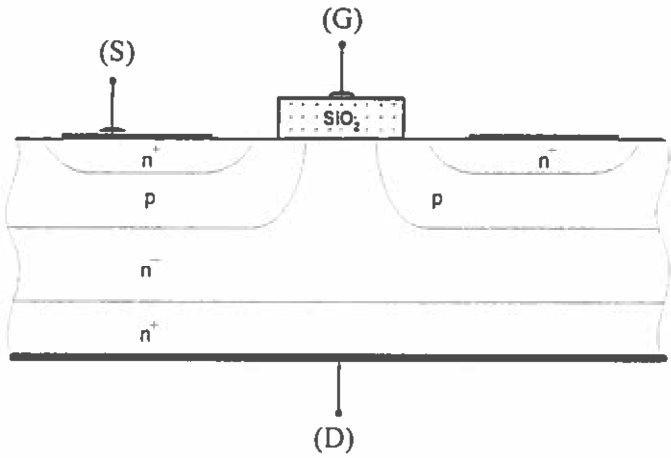

Figure 2.1: Material cross section of a power MOSFET.

a) A copy of fig. 2.1 is given on an additional sheet of paper. On this sheet answer the following questions:

i) Indicate the region(s) that will become the channel when the MOSFET is ON. [2]

ii) Indicate the parasitic BJT(s) within the structure by drawing the correct BJT symbol:  or  on the power MOSFET material cross section. [2]

iii) Give two reasons why this power MOSFET will not function properly. [4]

iv) Correct the structure to ensure optimal power MOSFET performance under normal operation conditions. [2]

b) Any power MOSFET suffers from high on-resistance.

i) Draw a diagram indicating the region in a power MOSFET that is associated with the JFET resistance and explain what increases this resistance when the MOSFET is ON. [5]

ii) Why does the IGBT not suffer from a high on resistance? Illustrate your answer. [5]

EE2-10A Devices – answer sheet for question 2a.
2016 exam

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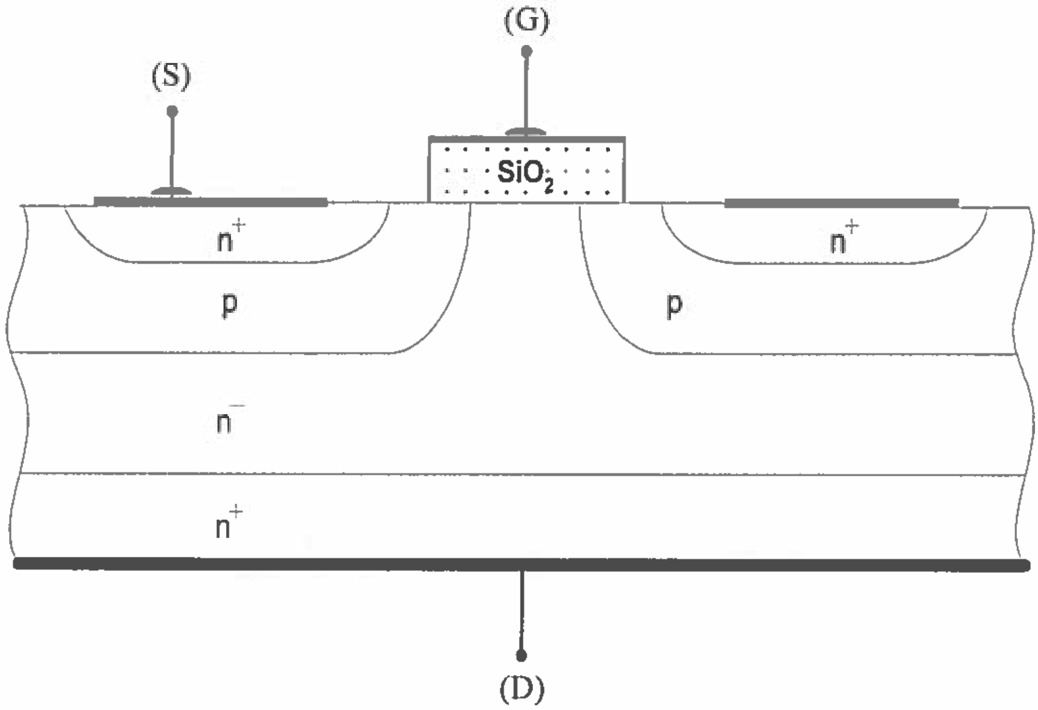

Figure 2.1: Material cross section of a possible power MOSFET.