IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2018

EEE PART II: MEng, BEng and ACGI

DEVICES

Corrected copy

Tuesday, 29 May 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) : W.T. Pike

Second Marker(s) : Z. Durrani

Special instructions for invigilators

Special instructions for students

Do not use red nor green ink.

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 $N_V = 1.8 \times 10^{19}$ 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. Generation and recombination in a pn diode.

a) Describe three processes that can cause recombination/generation of carriers in semiconductors, illustrating with a band diagram for each process. Which process is most commonly seen in silicon and why? [5]

b) By consideration of the diffusion current at the edge of the depletion region in a pn diode, derive an expression for the total current I_{tot} in a long diode and hence the value of the saturation current, I_s in the expression

$$I_{tot} = I_s[\exp(eV/kT)-1],$$

stating any assumptions you make. [7]

c) By consideration of excess charge in the quasi-neutral regions outside of the depletion region in a long pn diode, derive an alternative expression for I_{tot} and hence show the relationship between the carrier lifetime, the diffusion constant and the diffusion length. [4]

d) Minority carriers in a pn diode have a lifetime and diffusion constant of 40 μs and 10 cm²/s for electrons, and 60 μs and 25 cm²/s for holes. What are the minimum lengths of the n and p materials for the device to be considered in the long diode approximation? How might this change with an increased voltage across the diode, and why? [4]

2. A cross section of a lateral n- MOSFET and a portion of a n-channel DMOS array are shown below in fig. 2.1.

a) Write down what regions *a* through *o* represent, indicating the doping level where relevant. [8]

b) What is the state (accumulation, depletion or inversion) of regions *l1* and *m1* when the DMOS is on and off? [2]

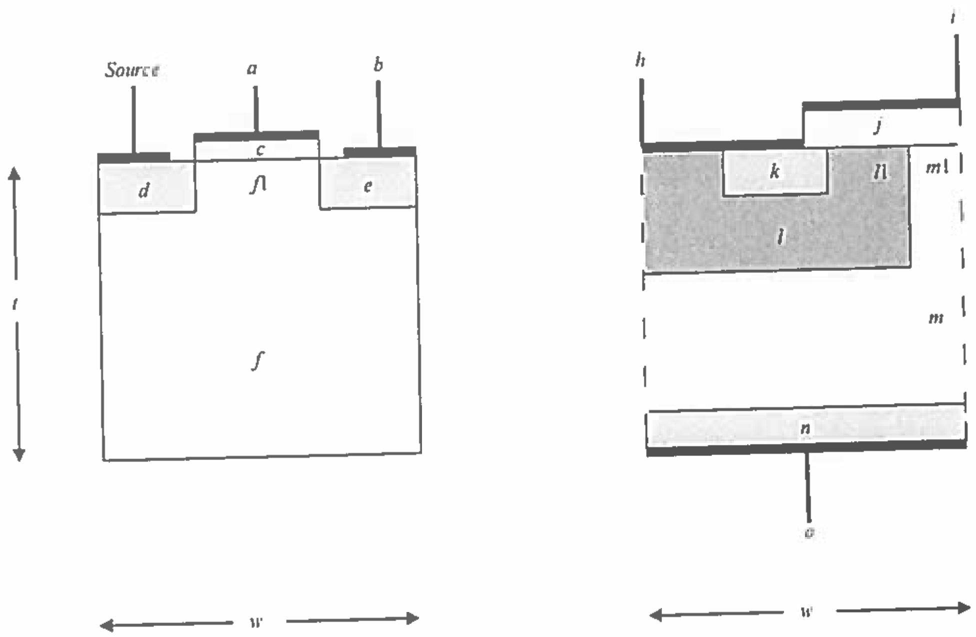
c) What type of contact is formed between the metal and semiconductor regions? [1]

d) Why is *h* connected to *l*? [2]

e) As width *w* is reduced, while the substrate thickness, *t*, remains constant, what advantages does the DMOS have over the MOSFET in handling larger currents? [2]

f) Why is *j* thicker than *c*? [1]

g) For the DMOS, draw the characteristic I_D vs. V_{DS} curves for a range of V_{GS}, indicating the linear/ohmic region, the saturation region and the breakdown region. [4]



n-MOSFET

Portion of n-channel DMOS

Figure 2.1: Cross sections of a n-MOSFET and a portion of an n-channel DMOS array. Metals are black, insulators white and doped semiconductors grey.