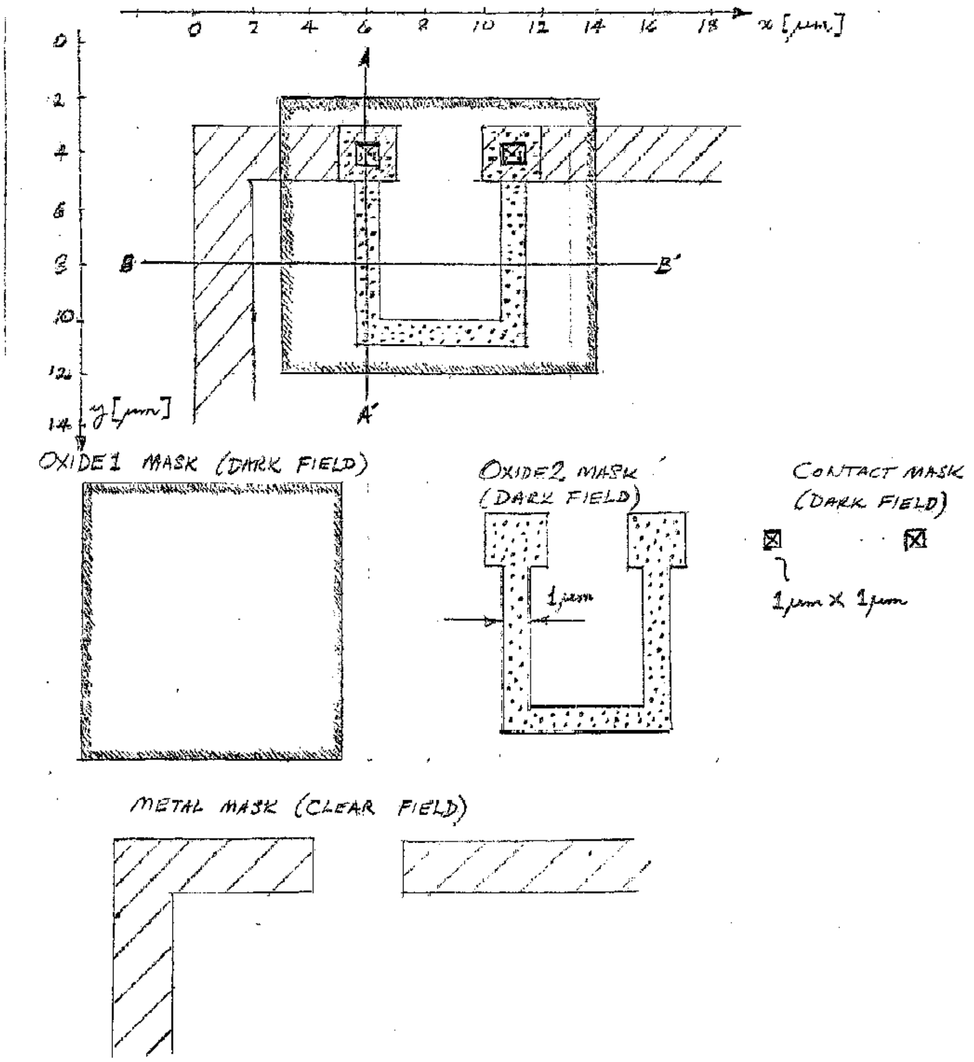
1. Resistor Layout [18 points]

The CAD layout for a resistor is shown below, along with the individual mask layers. For the Oxide1 mask, the *interior* of the rectangle is filled in ("colored") on the *CAD layout.*



Process Flow

0. Starting material: p-type silicon wafer, $N_a = 10^{16}\text{cm}^{-3}$.

1. Grow 0.5 μm of thermal SiO_2 and pattern using the **Oxide1 mask.**

2. Implant phosphorus (dose $Q_d = 5 \times 10^{12}\ \text{cm}^{-2}$) and anneal. The junction depth is $x_{j,1} = 1.5$ μm with the p-type substrate. The phosphorus does not penetrate the oxide.

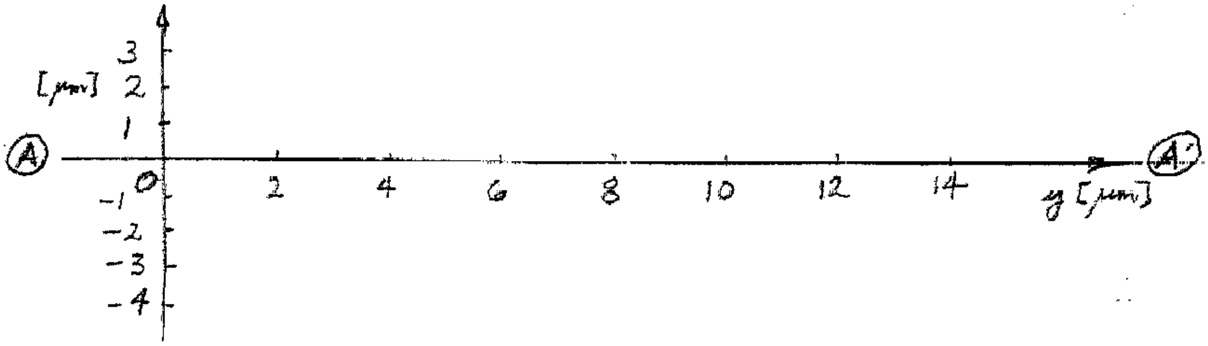
3. Deposit 0.5 μm of CVD SiO_2 and pattern using the **Oxide2 mask.**

4. Implant boron (dose $Q_a = 1.5 \times 10^{12}\ \text{cm}^{-2}$) and anneal to obtain a junction depth $x_{j,2} = 0.5$ μm with the n-type region formed in step 2. The boron does not penetrate the 0.5 μm-thick CVD oxide. During this anneal, the phosphorus penetrates further into the substrate and its junction depth with the substrate increases to $x_{j,1} = 2$ μm.

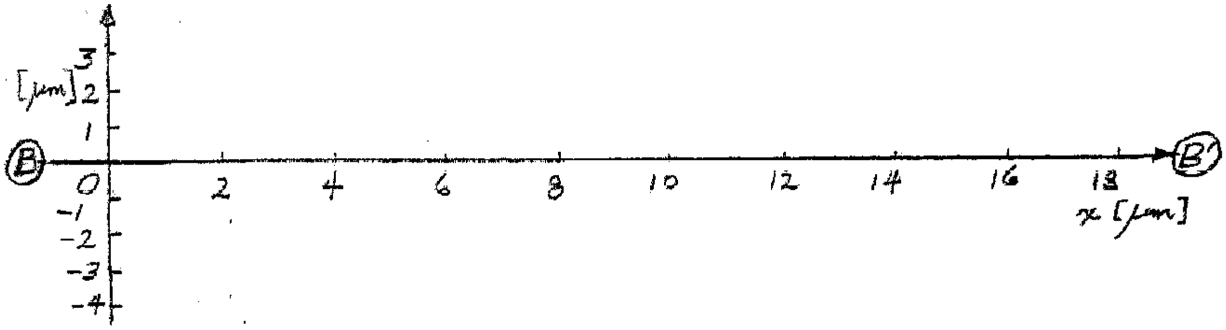
5. Deposit 0.5 μm of CVD SiO_2 and pattern using the **Contact mask.**

6. Deposit 1 μm of aluminum and pattern using the **Metal mask.**

(a) [6 pts.] Accurately sketch the fabricated structure along the cross section $A - A'$. Use the horizontal line below as the surface of the silicon wafer. The vertical scale should be followed in sketching the layers. Label all layers.



(b) [6 pts.] Accurately sketch the fabricated structure along the cross section $B - B'$. Use the horizontal line below as the surface of the silicon wafer. The vertical scale should be followed in sketching the layers. Label all layers.

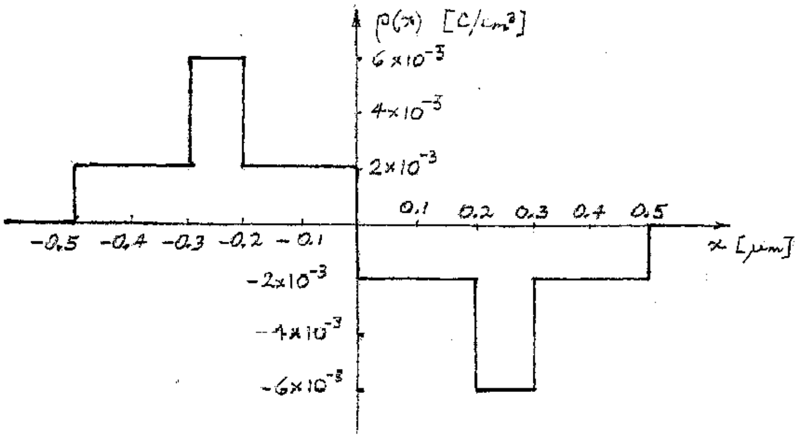


(c) [3 pts.] Find the average phosphorus concentration in the n-type region defined by the Oxide1 mask, after completion of the process.

(d) [3 pts.] Find the sheet resistance of the p-type region defined by the Oxide2 mask, after completion of the process. Note: the depletion region between the p and n regions penetrates 0.1 μm into the p-type layer.

2. Junction Electrostatics [17 points]

The depletion region in a p-n junction under a particular reverse bias voltage has a charge density given by



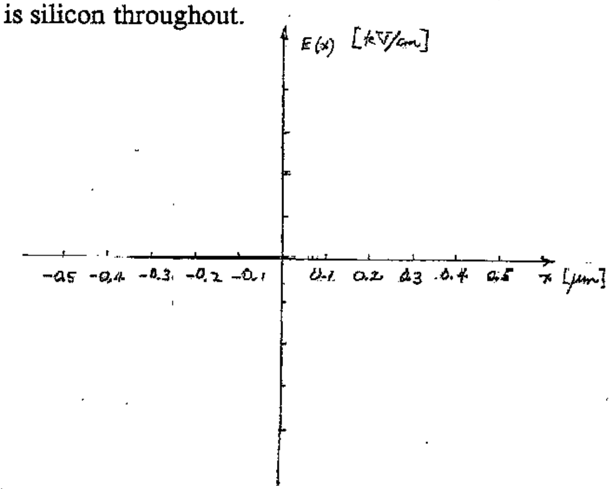
Given:

$q = 1.6 \times 10^{-19}$ C, $\varepsilon_s = 1.05 \times 10^{-12}$ F/cm,
1 μm = 10^{-4} cm

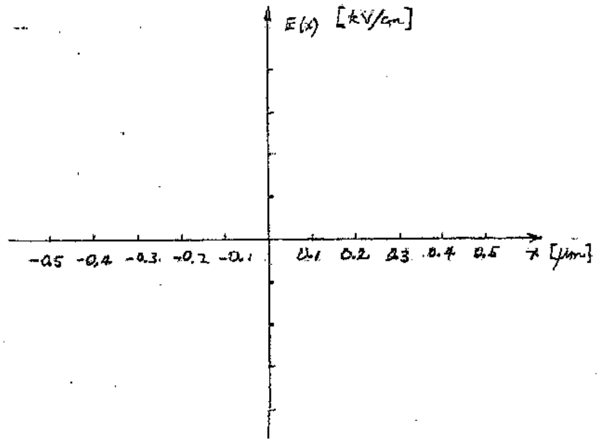
(a) [2 pts.] Which side of the junction (left, $x < 0$ or right, $x > 0$) is n-type and why?

(b) [4 pts.] Find the numerical value of the electric field at $x = 0$ in kV/cm, assuming that the material is silicon.

(c) [4 pts.] Plot the electric field $E(x)$ in the depletion region on the graph below, assuming that the material is silicon throughout.



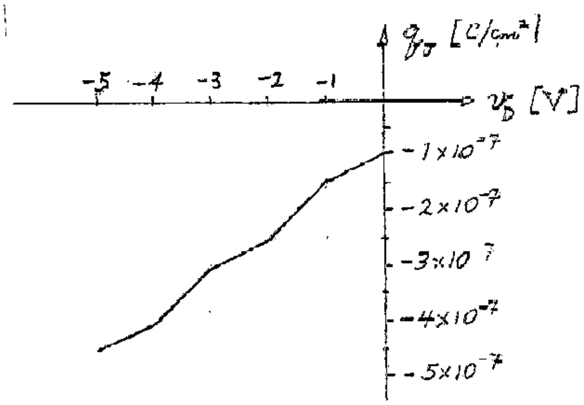
(d) [4pts.] For parts (d) and (e), we consider that the material on the left side of the junction ($x < 0$) is a silicon-germanium alloy with $\varepsilon_{sg} = 1.5 \times 10^{-12}$ F/cm. Replot the electric field $E(x)$ in the depletion region for this case on the graph below.



(e) [3 pts.] Find the numerical value of the depletion capacitance per area of the reverse-biased silicon-germanium/silicon junction.

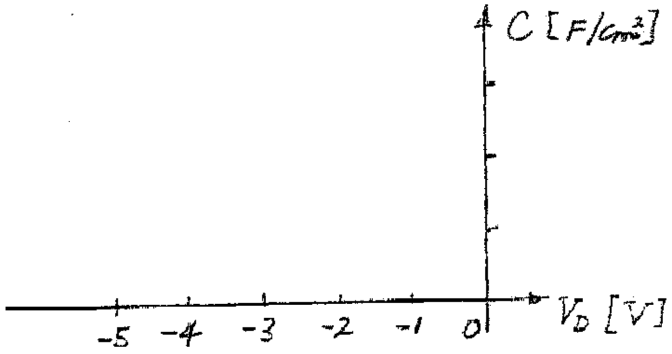
3. New junction capacitor [15 points]

The charge per unit area in a specially designed junction capacitor is given below.



(a) [3 pts.] What is the numerical value of the capacitance per unit area for V_D =0 V for this charge-storage element?

(b) [5 pts.] Plot the capacitance per unit area as a function of the DC bias voltage V_D on the graph below.



(c) [4 pts.] For a junction area of 10 μm X 20 μm and a bias voltage $V_D = -2.5$ V, find the small-signal current $i(t)$ into the junction capacitor for a small-signal voltage of $v_d(t) = 10\ \text{mV}\ \sin(2\pi 10^6 t)$.

(d) [3 pts.] What is the maximum amplitude of the sinusoidal voltage $v_d(t)$ for the small-signal approximation to remain accurate, at the bias voltage in part (c). Justify your answer.

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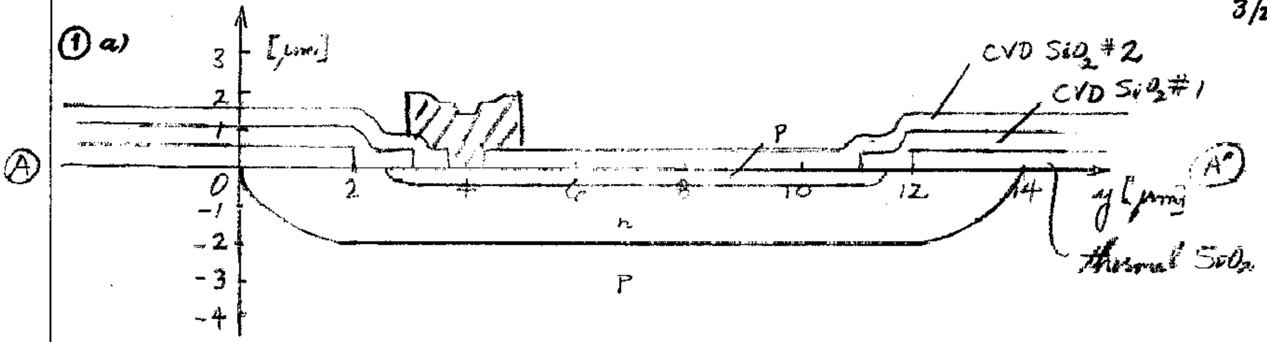
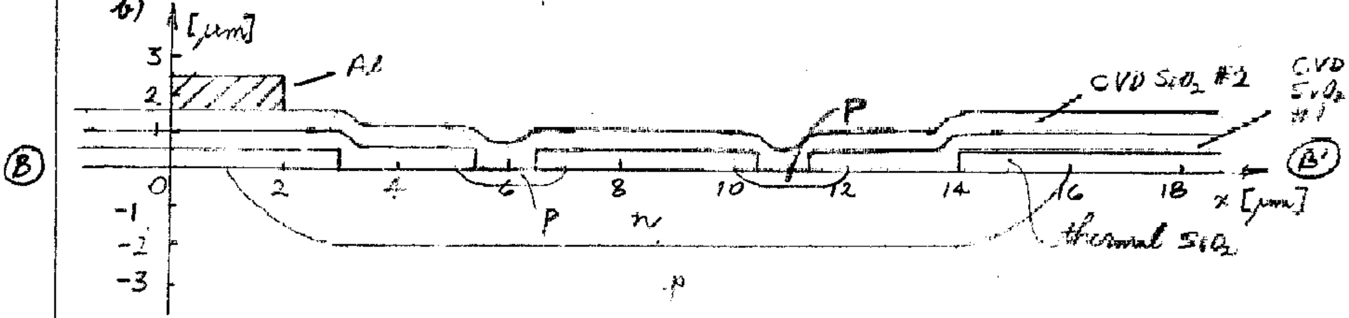
① a)



b)



c) Final junction depth = 2 μm
Implant dose of phosphorus = $Q_d = 5\times10^{12}\,cm^{-3}$ $\Big\}$ $\overline{N}_d = \frac{Q_d}{x_j} = 2.5\times10^{16}\,cm^{-3}$

d) Find hole concentration : $p = N_a - N_d = \underbrace{10^{16}\,cm^{-3}}_{\text{original boron conc.}} + \overbrace{\frac{1.5\times10^{12}}{0.5\times10^{-4}}}^{\text{implanted B}}\,cm^{-3} - 2.5\times10^{16}\,cm^{-3}$

$p = 4\times10^{16} - 2.5\times10^{16} = 1.5\times10^{16}\,cm^{-3}$

$t = x_j - x_p = 0.5\,\mu m - 0.1\,\mu m = 0.4\,\mu m$ = undepleted thickness of p region.

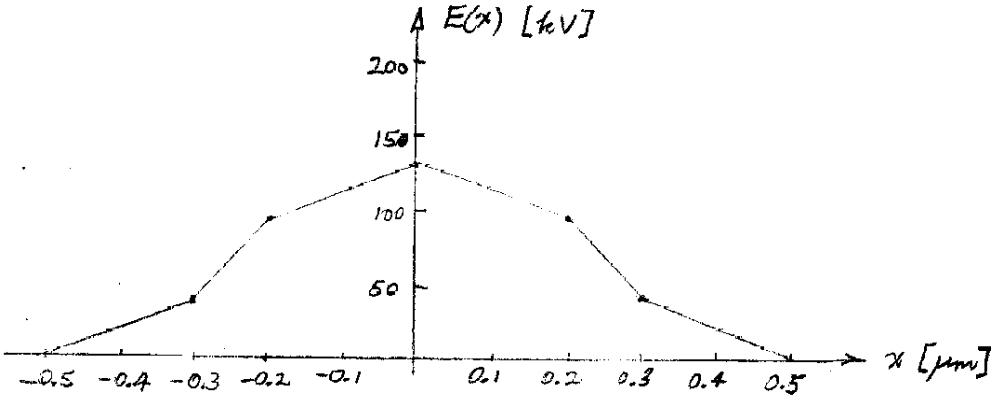
$R_\square = \frac{1}{q\mu_p\, p\cdot t} = \frac{1}{(1.6\times10^{-19})(400)(1.5\times10^{16})(4\times10^{-5})}\,\Omega/\square = 27\,k\Omega/\square.$

② a) $x < 0$ is n-type since depletion charge is positive there.

b) $E(x=0) = Q_{enc}/\epsilon_{Si} = \frac{(2\times10^{-3})(0.5\times10^{-4}) + (4\times10^{-3})(0.1\times10^{-4})}{1.05\times10^{-12}}$

$= \frac{1.4\times10^{-7}}{1.05\times10^{-12}} = 1.3\times10^{5}\,V/cm = 130\,kV/cm$

c)



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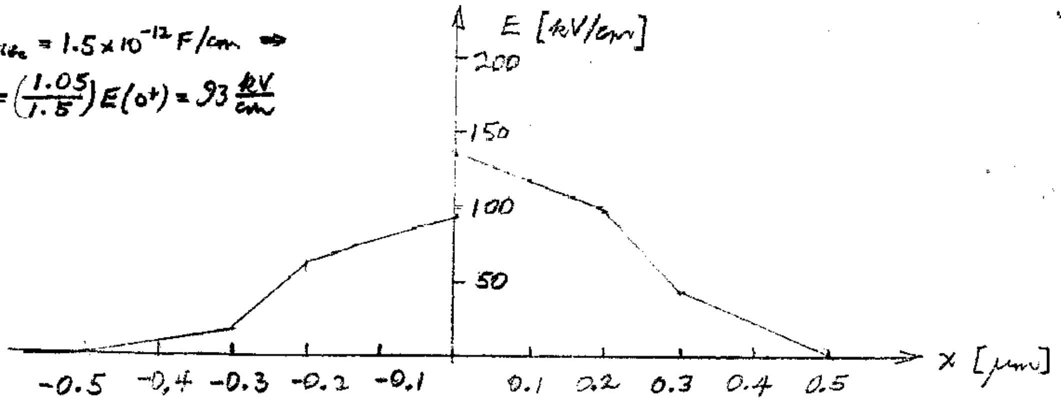
d) $\epsilon_{SiGe} = 1.5 \times 10^{-12}$ F/cm $\Rightarrow$

$E(0^-) = \left(\frac{1.05}{1.5}\right) E(0^+) = 93 \frac{kV}{cm}$



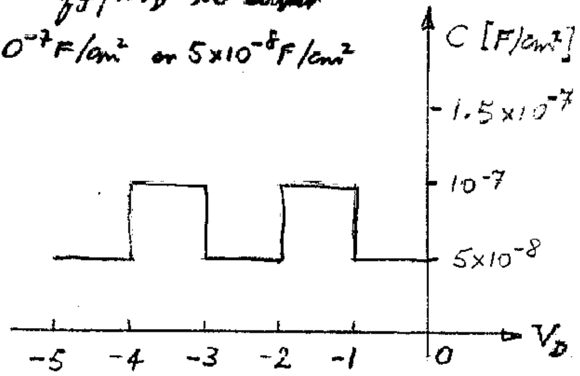
e) C = series combination of a SiGe depletion region (0.5μm) and a Si depletion region.

$$C = \left(\frac{\epsilon_{SiGe}}{0.5\,\mu m}\right) \| \left(\frac{\epsilon_{Si}}{0.5\,\mu m}\right) = \left(\frac{1.5 \times 10^{-12} F/cm}{0.5 \times 10^{-4}\ cm}\right) \| \left(\frac{1.05 \times 10^{-12} F/cm}{0.5 \times 10^{-4} cm}\right) = 1.26 \times 10^{-8} F/cm^2 = 126\,nF/cm^2$$

③ a) $C(V_D = 0) = dq_J / dv_D \big|_{V_D = 0V}$

$$= \frac{0.5 \times 10^{-7} C/cm^2}{1V} = 5 \times 10^{-8} F/cm^2 = 0.5\,fF/\mu m^2$$

b) dq_J/dv_D is either $10^{-7} F/cm^2$ or $5 \times 10^{-8} F/cm^2$



c) Area $= 10 \times 20\,\mu m^2 = 200 \times 10^{-8} cm^2 \Rightarrow C\big|_{V_D = -2.5V} = (5 \times 10^{-8} F/cm^2)(2 \times 10^{-6} cm^2)$

$C = 10^{-13} F = 100 fF.$

$i = C \frac{dv_d}{dt} = \omega C \hat{v}_d \cos \omega t$

$\omega = 2\pi \times 10^6$ rads^{-1}

$\hat{v}_d = 10mV = 10^{-2} V$

$\therefore i = (2\pi \times 10^6 \times 10^{-13} \times 10^{-2} A) \cos \omega t$

$i = (6.3\,nA) \cos \omega t$

d) From answer to (b), the slope of $q_J(v_D)$ is constant from $v_D = -3V$ to $v_D = -2V$. $\therefore$ $\hat{v}_d \big|_{max} = 500\,mV = 0.5V$ since for $V_D = -2.5V$, $v_D = V_D \pm \hat{v}_d$ must remain in this interval.