Task 1

Ferroelectric Field Effect Transistor (FEFET) modelling using Miller/Preisach Model.

A. Modelling Hysteresis in Ferroelectrics.

(1) Modelling hysteresis (Fig. 1.1) using following equations

$$Q_L(V) = \frac{C}{2a}\left[arctan\left(\frac{V_M+V_C}{a}\right) - arctan\left(\frac{V_M-V_C}{a}\right)\right] + \frac{C}{a}.arctan\left(\frac{V_M-V}{a}\right). \text{ Lower branch} \quad (1.1)$$

$$Q_U(V) = \frac{C}{2a}\left[arctan\left(\frac{V_M-V_C}{a}\right) - arctan\left(\frac{V_M+V_C}{a}\right)\right] + \frac{C}{a}.arctan\left(\frac{V_M+V}{a}\right) \text{ Upper branch} \quad (1.2)$$

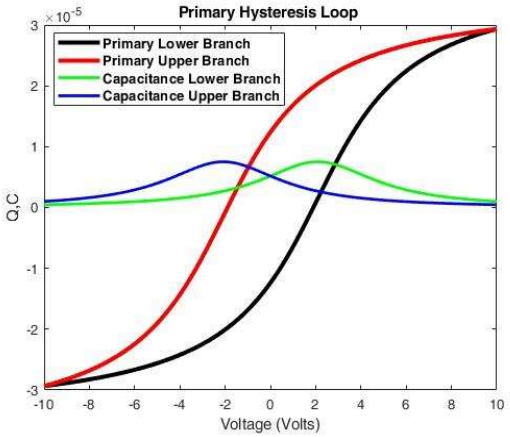

Fig. 1.1 saturated hysteresis loop

(2) Modelling Lower and upper branch minor loops (as shown in Fig. 1.2) are formulated as

$$Q'_L(V) = \frac{C'}{2a}\left[arctan\left(\frac{V_X+V_C}{a}\right) - arctan\left(\frac{V_X-V_C}{a}\right)\right] + \frac{C}{a}.arctan\left(\frac{V_X-V}{a}\right) \text{ Lower branch} \quad (1.3)$$

$$Q'_U(V) = \frac{C'}{2a}\left[arctan\left(\frac{V_X+V_C}{a}\right) - arctan\left(\frac{V_X\mp}{a}\right)\right] + \frac{C}{a}.arctan\left(\frac{V_X+V}{a}\right) \text{ Upper branch} \quad (1.4)$$

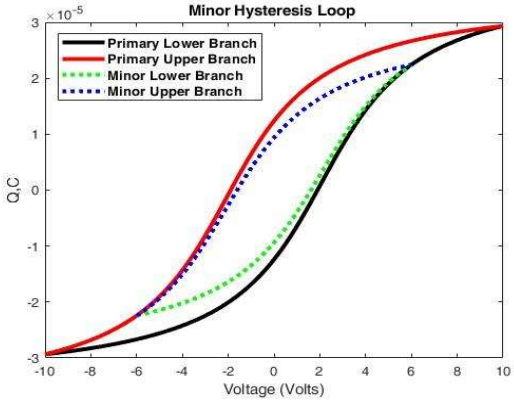

Fig. 1.2 Minor hysteresis loop

(3) Use analytical model described in equations (1.1) - (1.4) to implement the Preisach model. Fig. 1.3 shows implementation of the Preisach model where the electric field depolarizes the ferroelectric. *Model to generalizing polarization and depolarization curve based on memory*.
(4) Incorporation of time variation in the Preisach Model.

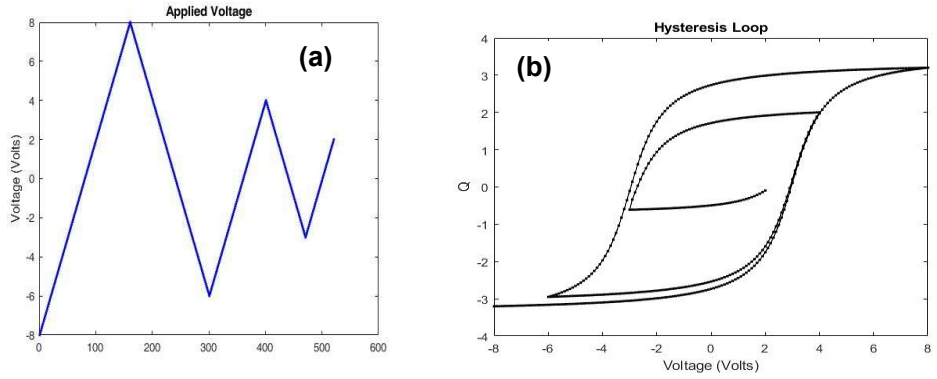

Fig. 1.3 (a) Applied electric field across ferroelectric and (b) depolarization curve obtained from Preisach model

B. Integration of the Preisach model into the ferroelectric field-effect transistor (FEFET) device architecture utilizing the self-consistent loop method to calculate charge and potential in the semiconductor channel. Fig. 1.4 shows steps for computing charge and potential in FEFET structure using Preisach model.

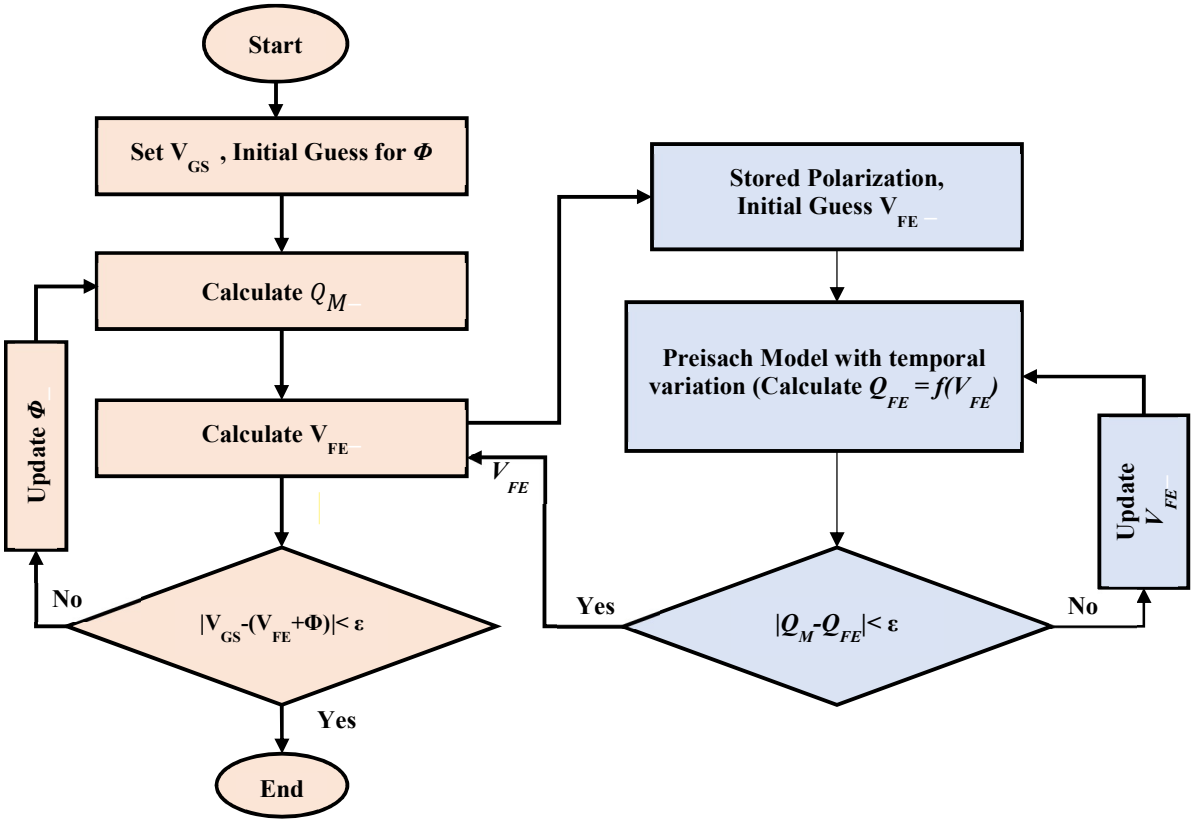

Fig. 1.4 Flow chart for solving electrostatic in FEFET self consistently.

Task 2

Phase field Modelling of FEFET using Time Dependent Ginzburg Landau (TDGL) Equation.

A. Computing Potential using Poisson's equation in the Ferroelectric layer.

$$\in_f \left(\frac{\partial^2 \emptyset}{\partial x^2} + \frac{\partial^2 \emptyset}{\partial y^2}\right) = \frac{\partial P}{\partial x} + \frac{\partial P}{\partial y} \quad (2.1)$$

B. Where P is polarization and ϕ is potential in the Ferroelectric layer. Potential ϕ will be computed iteratively given initial value of P.

C. Computing Polarization, P (using TDGL equation) from the potential calculated from Poisson's equation (2.1).

$$\Gamma \frac{dP}{dt} = \alpha P + \beta P^3 + \gamma P^5 - \kappa_1 \frac{\partial^2 P}{\partial x^2} - \kappa_2 \frac{\partial^2 P}{\partial y^2} + \frac{\partial \phi}{\partial x} + \frac{\partial \phi}{\partial y} \quad (2.2)$$

D. Solving Poisson's equation in the oxide layer.

$$\left(\frac{\partial^2 \emptyset}{\partial x^2} + \frac{\partial^2 \emptyset}{\partial y^2}\right) = 0 \quad (2.3)$$

E. Computing potential in Semiconductor using Poisson's equation

$$\in_{Si} \left(\frac{\partial^2 \emptyset}{\partial x^2} + \frac{\partial^2 \emptyset}{\partial y^2}\right) = \rho \quad (2.4)$$

F. Computing Charge in Semiconductor layer.

$$\rho(x,y) = e(n_p - p_n + N_d^+ - N_a^-) \quad (2.5)$$

$$p_n(x,y) = N_C \, e^{-\frac{(E_C - e\phi)}{K_B T}} \quad (2.6)$$

$$n_p(x,y) = N_V \, e^{-\frac{(e\phi - E_V)}{K_B T}} \quad (2.7)$$

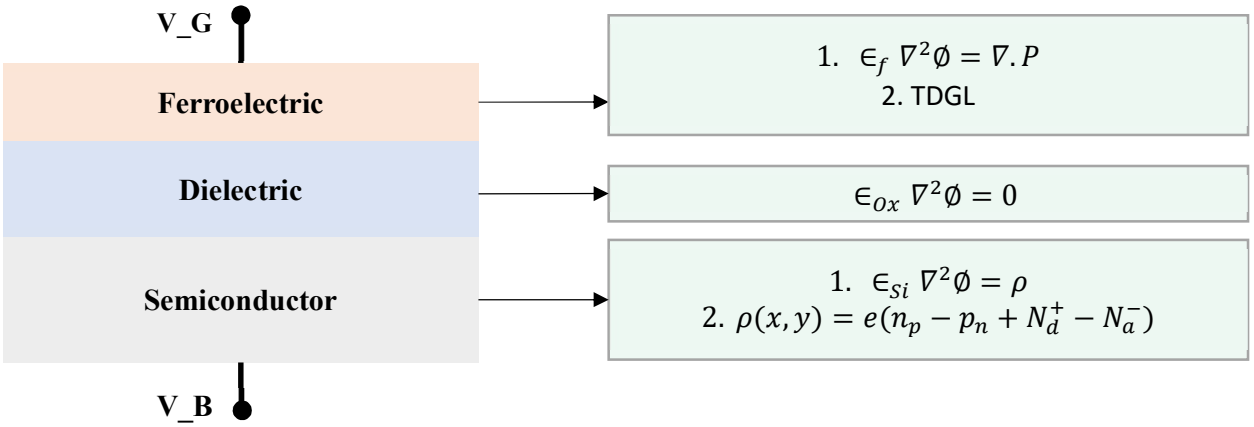

Fig. 2.1 Device structure to be modelled.

The electrostatic described by the equations 2.1-2.7 has to be simulated numerically for the layers shown in Fig. 2.1. Simulation is divided into two steps: (1) initialization step for static condition and, (2) Time dependent Simulations for varying gate voltage.

Initialization: Initialize Polarization *P*, Compute Potential in the device structure as depicted in Fig. 2.2 for 0 V applied.

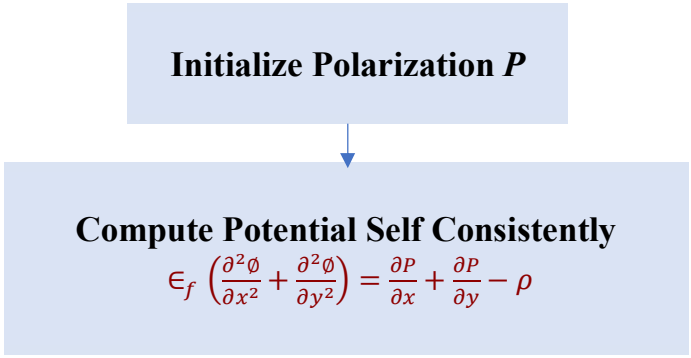

Fig. 2.2 Initialization step.

Time Dependent Simulations:

1. Compute $P(k+1) = P(k) + \Delta t\, f(P(k), \phi(k))$ using TDGL eqn. 2.2.
2. Compute $\phi(k+1)$ using Poisson's equation.
3. Compute Charge density in semiconductor using equation 2.5 and 2.6.

Step 1 to 3 to be computed self consistently as depicted in Fig. 2.3

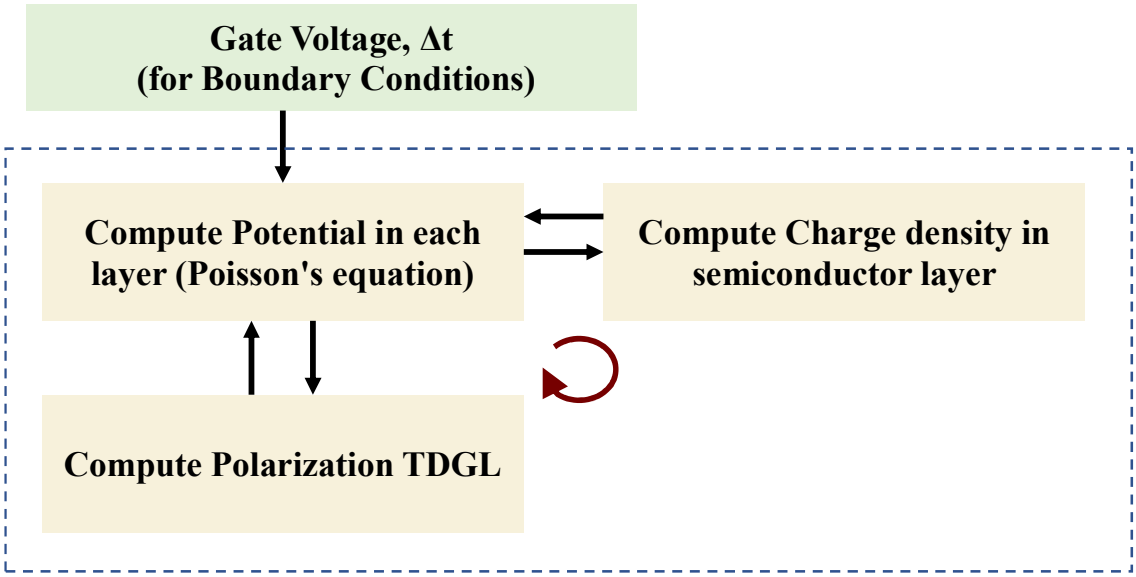

Fig. 2.3 Time dependent electrostatic computation steps in MFIS structure.