Dopingfree Schottky Buried Metal Layer Fully Depleted Planar FET for SCE Suppression at sub-28nm Technology Nodes

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Dopingfree Schottky Buried Metal Layer Fully Depleted Planar FET for SCE Suppression at sub-28nm Technology Nodes

Design, Simulation and Performance Investigation

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Abstract Herein we introduce and investigate a new architectural design strategy for planar single gate field effect transistors (SG-FETs) that delivers advantages from all fronts of design, fabrication and performance perspectives. The amalgamation of schottky buried metal layer (BML) and charge plasma (CP) mechanism of doping in planar single gate architecture yields a novel type of FET called as CP-BML FET. Owing to the schottky BML induced depletion region created on the bottom side of device layer reduces effective device layer thickness (T_{Si}) suppressing short channel effects (SCEs) including drain induced barrier lowering (DIBL) and threshold voltage roll-off. The proposed FET has been analyzed for DC and RF performance figure of merits (FOMs) and compared to counter part state of the art technologies with reference to ITRS performance projections. The proposed FET is also investigated the performance FOMs on for criticality of physical parameters including gate length (L_g), device layer thickness (T_{Si}), BML workfunction (ϕ_{BML}). The I_{ON} and I_{OFF} for proposed device at $L_g = 20\text{nm}$ read at $730\mu\text{A}/\mu\text{m}$ and $7 \times 10^{-2} \text{ pA}/\mu\text{m}$ respectively. RF performance analysis reveal transition frequency (f_t) of 390 GHz with $SS \simeq 75\text{mV}/\text{dec}$ coherent with ITRS performance projections. It is found that ultra scaled (7 nm) proposed device exhibits intrinsic delay τ of 0.6 ps which is superior to ITRS projections of 1.71 ps at 28 nm technology node. The proposed device yields P_{dyn} of $0.248 \text{ fJ}/\mu\text{m}$ at $L_g=7\text{nm}$ implicating it to be potential candidate for low power with high performance application requirements.

Keywords Buried metal layer (BML) · Charge plasma · Dopingfree · Junctionless field effect transistor (FET) · Scaling · SCEs (short channel effects) · Workfunction.

1 Introduction

The progress in semiconductor device technology imposes physical limits on scaling that renders adhesion to Moore's law. Following Moore's law, the incessant scaling of classical CMOS (complementary metal oxide semiconductor) technology transistor is accompanied by short geometry effects (SCEs) [1]. With scaling of gate length (L_g), SCEs hold a critical role in determining the performance of transistors especially for RF applications. For technology nodes below 28 nm, classical CMOS approach fails to live upto the minimum requirements of various performance metrics that include OFF state current (I_{OFF}), subthreshold swing (SS), $\frac{I_{ON}}{I_{OFF}}$ ratio, drain induced barrier lowering (DIBL), transition frequency (f_t), power dissipation [2]. Sub-22 nm technology nodes suffer heavily with limitations of perfect abrupt doping profiles which in-turn yields in performance that does not comply with international technology roadmap of semiconductors (ITRS) projections [3]. Already several technologies different from conventional CMOS have been implemented at industry level that comply with ITRS standards like FinFETs, multi-gate FETs, junctionless FETs etc [4].

Scaling has been classified on time scale as geometrical scaling (1975-2002: proportional scaling down of geometrical dimensions for planar architectures), equivalent scaling (2003-2025: down scaling of only horizontal feature size (L_g)) and 3D power scaling (2025-2040: vertical device architectures) [5]. The current era of

equivalent scaling paves the way for introduction of new materials along with exploration of physical effects for new device architectures whilst maintaining ITRS performance projections [6]. ITRS 2026 projects the maximum I_{OFF} of 5 nA/ μm , I_{ON} of 0.6 mA/ μm , intrinsic gate delay of 0.26 ps for low operating power devices [7]. Various architectural modifications exploring new realms of device physics have been proposed in the last decade. One of such techniques is the junctionless transistor (JLT) where the depletion in the channel is induced by the gate workfunction engineering in the OFF-state [8]. The channel of JLT consists of uniform high doping throughout source-channel-drain regions eliminating the requirement of abrupt/steep junction doping profiles [9, 10]. However this device kind of architecture is not fruitful in single planar structures where efficient volume depletion is not achieved [11, 12]. Moreover due to high doping requirements typically of the order of 10^{19} cm^{-3} , the device fabrication requires high thermal budget with complex ion implantation process which become even more tedious at lower technology nodes [11].

The concept of virtual doping against the conventional chemical doping technique is imbibed from the concept of contact electrode workfunction engineering called charge plasma engineering that induces high density charge carriers in intrinsic semiconductors using electrodes of appropriate workfunction [13]. This provides the relaxation from requirement of high doping whilst maintaining high I_{ON} and low I_{OFF} [14, 15]. In single gate planar device architectures, introduction of buried metal layer (BML) with realization of schottky junction at the bottom side provides superior depletion limiting OFF-state current [16]. The amalgamation of charge plasma engineering with BML in planar device architectures provides window for equivalent scaling whilst meeting the ITRS performance requirements even upto 7nm technology node.

Deliverables and Organization of this work

In this work, we propose a new geometrically planar field effect transistor with a single gate controlled channel delivering the performance compared to that of multi-gate FETs more importantly following ITRS requirements. The proposed device exhaustively uses the geometrical advantages of SOI FETs delivers a superior FET when designed in conjuncture with charge plasma technique relieving the fabrication scheme from high budget doping process. The use of Schottky buried metal layer realizes complete depletion of the channel limiting Off-state current to minimum eliminating one of the main liabilities of single gate planar architecture FETs. The report is organized as, in Section 2, the device

architectural specifications along with parameters for experimental calibration are discussed. The proposed device is analyzed for DC as well as RF conditions presented in Section 3. The performance is compared to state of art devices given in Section 3.4. The overall performance of the proposed device is at par with the requirements by ITRS considerations.

Fig. 1 (a) Conventional bulk planar junctionless SOI FET [17], (b) Bulk planar junctionless with buried metal layer FET, (c) Proposed charge plasma induced dopingless source drain fully depleted buried metal layer planar FET (d) Experimental calibration of simulation model for BP-JLT with [17].

2 Device Architectural Specs, Simulation Methodology and Experimental Calibration

Figure 1 (a-c) shows the device architectural variations from schematics in the conventional bulk planar junctionless SOI FET, the bulk planar junctionless with buried metal layer SOI FET and the proposed FET with schottky BML where the source and drain regions are realized by charge plasma concept of virtual doping. Table 1 lists all the physical parameter specifications of the proposed and compared counterpart device. High doping concentration of 10^{19} cm^{-2} throughout source, channel and drain regions in the junctionless FET ensures high On-state current where as the gate workfunction (ϕ_G) is chosen such the complete depletion is attained in Off-state ensuring sufficient $\frac{I_{ON}}{I_{OFF}}$ ratio. For single gate conventional MOS devices, the gate control on the channel is feeble and the extent of which is limited into the channel depth. This leads to enhanced I_{OFF} , thereby limiting the power consumption performance of the device. The inception of schottky buried metal layer (BML) is to virtually reduce the effective device layer thickness in single gate devices to enhance the gate control on the channel by creating a space charge region with no mobile ions on the bottom side of device layer.

Table 1 Physical parameter specification of junctionless buried metal layer FET (JL-BML-FET) and proposed charge plasma dopingless buried metal layer FET (CP-BML-FET).

Parameter (Symbol)	JL-BML-FET	CP-BML-FET
Gate Length (L_G)	20 nm	20 nm
Drain Length (L_D)	20 nm	20 nm
Source Length (L_S)	20 nm	20 nm
Buried Oxide Thickness (T_{Box})	50 nm	50 nm
Effective gate Oxide Thickness (T_{ox})	0.8 nm	0.8 nm
Device Layer Thickness (T_{Si})	10 nm	10 nm
Gate Workfunction (ϕ_G)	5.12 eV	4.12 eV nm
Source/Drain contact Workfunction (ϕ_M)	4.12 eV	3.9 eV nm
Doping Concentration Device Layer (N_D)	10^{19}cm^{-2}	10^{16}cm^{-2}
Buried Metal Layer Workfunction (ϕ_{BML})	5.2 eV	5.2 eV

A sufficient schottky barrier height (ϕ_{BH}) ensures the formation of depletion region, the depth of which is a function of workfunction of buried metal layer (ϕ_{BML}). The extent of depletion region by schottky BML is given by Eq. 1.

$$y_{\text{dep,BML}} = \sqrt{\frac{2\epsilon_{Si}}{qN_D} \{q(\phi_{BML} - \phi_{Si}) - V_T - V_{BML}\}} \quad (1)$$

In above Eq. 1, ϵ_{Si} , N_D , q , ϕ_{Si} , V_T , V_{BML} represent permittivity of silicon, device layer doping concentration, electron affinity of silicon, thermal voltage and voltage applied at buried metal layer. As indicative in the equation, for higher doping concentrations, the workfunction of BML to effectively create the depletion region, BML with high workfunction is required which may not be feasible. The workfunction of BML is chosen such that $\phi_{BML} - \phi_{Si} > 0$, where $\phi_{Si} = \chi_{Si} + \frac{E_G}{2} + \frac{KT}{q} \ln \frac{N_D}{N_i}$. Since the inception of minimization of semiconductor devices, chemical doping and associated annealing procedures pose challenge to scaling of technology [6]. The doping and annealing processes are essentially carried out in high temperatures not only increasing the thermal budget but may render the device useless at small technology nodes by oxidation and uncontrolled ion activation [10]. The formation of high carrier concentration regions in moderately intrinsic device layer by workfunction engineering of contact electrodes forbids the use of chemical doping and annealing techniques in the fabrication process [15,18]. The formation of charge plasma (electron or hole plasma) in the semiconductor depends on following two essential conditions:

1) For electron plasma formation, $\phi_{S/D} > (\chi_{Si} + \frac{E_{G,Si}}{2})$. To form the hole plasma, $\phi_{S/D} < (\chi_{Si} + \frac{E_{G,Si}}{2})$ [14,19]. In this work hafnium with workfunction of 3.9 eV have been used as source and drain contact electrodes creating electron plasma in moderately intrinsic semiconductor. 2) The thickness of the semiconductor layer (t_{Si}) must be less than Debye's length

($\lambda_D = \sqrt{\frac{\epsilon_{Si} V_T}{q N_D}}$). For every λ_D addition to t_{Si} , the electric field by contact electrode is screened by $\frac{1}{e}$ [13].

2.1 Simulation Framework and Experimental Calibration

For credible and reliable simulation results, various models have been invoked in Atlas Silvaco collectively. The different in-built models invoked during the simulations account for different carrier transport phenomena. Highly doped devices are prone to bandgap narrowing where the change in energy bandgap (ΔE_G) becomes doping concentration dependent which in turn affects the electron affinity (χ) of the material, such effects are simulated by invoking BGN model in the simulator. Prior to BGN it is important to consider the carrier transport physics which is taken care by FERMI-DIRAC model which solves Boltzmann's-Fermi Dirac statistics for charge carriers with different energy levels. Shockley-Read-Hall (SRH) and AUGER models for recombination are also included in the simulation framework. Bulk planar junctionless FET (BP-JLT) has been reproduced and the parameters which include energy band density of states (NC300, NV300), carrier lifetimes (electron lifetime: TAUN0, hole lifetime: TAUP0), interface charges, in simulation model have been adjusted to achieve the experimental characteristics of BP-JLT in [17] as shown in Fig. 1(d). The carrier life times (τ_p , τ_n) were set to be $10^{-1} \mu s$. The energy band density of states (N_C , N_V) at 300°K are taken as $2.8 \times 10^{19} \text{cm}^{-3}$ and $1.04 \times 10^{19} \text{cm}^{-3}$ respectively. The electron and hole thermal velocities (V_n , V_p) were set to be $1.08 \times 10^7 \text{cm/s}$ and $1.3 \times 10^7 \text{cm/s}$ respectively considering saturation velocities to be equal.

3 Simulation Results and Discussion

The performance metrics for the proposed charge plasma BML FET under for DC and AC conditions have been

evaluated and extensively studied for dependence in physical parameters that include scaling (L_g), BML workfunction (ϕ_{BML}), device layer thickness (t_{Si}). On the basis of performance metrics that include DIBL, I_{ON} , I_{OFF} , I_{ON}/I_{OFF} , SS, transconductance (g_m), output conductance (g_d), C_{gs} , C_{gd} , f_t , f_{max} , GBP, A_V , TGF, TFP, τ , and P_{dyn} , the performance of proposed device has been compared with counterpart technologies particularly at sub-28nm technology nodes.

3.1 DC Performance Analysis

Fig. 2 (a). Horizontal energy band variation for JL-BML-SOI FET in OFF and ON state, (b). Horizontal energy band variation for CP-BML-SOI FET in OFF and ON state, (c). Vertical energy band variation in channel for JL-BML-SOI FET in OFF and ON state, (d). Vertical energy band variation in channel for CP-BML-SOI FET in OFF and ON state. OFF state @ $V_{gs} = 0V$, $V_{ds} = 1.2V$, ON state @ $V_{gs} = 1.2V$, $V_{ds} = 1.2V$.

The horizontal and vertical variations in energy band levels for ON-state (V_{GS} , $V_{DS} = 1.2V$, $1.2V$) and OFF-state (V_{GS} , $V_{DS} = 0V$, $1.2V$) for CP-BML FET and JL-BML FET are shown in Fig. 2(a-d). In OFF-state there is a barrier height of 0.72V for majority carriers in CP-BML FET while as barrier height of 0.6V is observed in JL-BML FET leading to enhanced gate control in former device. The horizontal energy band variations reveal the absence of tunneling path in OFF-state minimizing the OFF-state current even at 20nm technology node. The vertical energy band variation across the gate oxide and device layer are almost same except that band bending for JL-BML FET is more than CP-BML FET due to high workfunction gate ($\phi_G = 5.1eV$) in the junctionless FET. Fig. 3(a) show the transfer characteristics for proposed CP-BML FET and JL-BML FET

for $L_g = 20$ nm at $V_{DS} = 1.2V$. The I_{ON} and I_{OFF} for CP-BML FET read at $730\mu A/\mu m$ and $7 \times 10^{-2} pA/\mu m$ respectively while for JL-BML FET I_{ON} and I_{OFF} read at $0.4 \mu A/\mu m$ and $0.2 pA/\mu A$ respectively. At $L_g = 20$ nm, and driving voltage $V_{DS} = 1.2V$, CP-BML FET has superior $\frac{I_{ON}}{I_{OFF}}$ ratio of 10^{11} against 10^8 for JL-BML FET which satisfies the ITRS 2025 requirement. The steeper SS ($= 2.3V_T(1 + \frac{C_{dm}}{C_{ox}})$) of 75mV/dec and low OFF-state current in CP-BML FET is owed to smaller depletion capacitance (C_{dm}), also the channel controllability of gate is firm due to weak penetration of depletion regions formed by charge plasma induced source/drain regions and depletion in device layer due to schottky BML. Figure 3(b) compares transconductance at $V_{DS} = 1.2V$ for CP-BML FET and JL-BML FET. It reveals high g_m of $1.4 mS/\mu m$ and $0.65 mS/\mu m$ for CP-BML FET and JL-BML FET observed at 0.825 V and 1.05V respectively. g_m is a metric to estimate the ability of a device to convert gate voltage to drain current. A low value of g_m indicates mobility degradation which generally follows high electric field and high g_m is indicative of efficient switching times. Maximum output conductance ($g_{d,max}$) of $0.25 mS/\mu m$ is observed for CP-BML FET while as $0.12 mS/\mu m$ is observed for JL-BML FET at $L_g = 20$ nm.

Fig. 3 (a) Transfer characteristics for JL-BML FET and CP-BML FET indicating V_{Th} and I_{OFF} at $L_g = 20$ nm. (b) Transconductance characteristics for JL-BML FET and CP-BML FET at $L_g = 20$ nm.

Figure 4(a-d) depict the the electron concentration in the silicon device layer of $t_{Si} = 10$ nm for JL-BML FET and CP-BML FET in ON and OFF state. The formation of conducting path (high electron concentration layer) between source and drain regions when the devices are turned from OFF state to ON-state can be observed. For JL-BML FET, in OFF-state the high concentration regions are rendered under source and drain electrodes, the channel area under the influence of high ϕ_G of gate is depleted of free charge carriers. On the onset of V_{GS} , the conducting channel is formed as the flat-band voltage is achieved. In CP-BML FET, the device layer has N_D of $10^{15} cm^{-3}$, where the high concentration source and drain regions are formed by

charge plasma engineering. The role of BML at the bottom side of device layer creates a schottky junction (depletion region), rendering the charge carrier to surface of the channel in both devices. Since workfunction of silicon (ϕ_{Si}) is dependent on doping N_D , device with high $N_D = 10^{19} \text{cm}^{-3}$ (JL-BML FET) has small depletion layer width than device with low $N_D = 10^{15} \text{cm}^{-3}$ (CP-BML FET). The twofold advantages of introducing a schottky BML include more channel controllability which significantly improves SS and channel thickness variability yielding small DIBL. The schottky barrier height at BML-Si junction significantly affects DIBL of the device as it controls the potential and charge distribution in the channel region. For BML with same ϕ_{BML} in CP-BML FET and JL-BML FET, larger depletion region is formed in CP-BML FET minimizing I_{OFF} and DIBL equal to 0.2 pA/ μA and 20 mV/V respectively.

Fig. 4 Contour diagrams showing electron concentration for (a) JL-BML FET in OFF state, (b) JL-BML FET in ON state, (c) CP-BML FET in OFF state, (d) CP-BML FET in ON state.

3.2 RF Performance Analysis

Intrinsic capacitances that include gate to source capacitance (C_{gs}) and gate to drain capacitance (C_{gd}) largely affect the frequency performance FOMs of any CMOS devices. Since $C_{gs} > C_{gd}$, C_{gd} is considered as parasitic or Miller capacitance. It must also be noted that the parasitic capacitance is device geometry dependent that is for multi-gate devices, the parasitic capacitance may be different. The variation of C_{gs} , C_{gd} w.r.t. V_{GS} for JL-BML FET and CP-BML FET is shown in Fig. 5(a-b). In ON-state for $L_G = 20 \text{nm}$, C_{gs} and C_{gd} for JL-BML FET are found to be 0.65 fF/ μm and 0.114 fF/ μm whereas for CP-BML FET are 0.69 fF/ μm and 0.113 fF/ μm respectively. One of the important FOM is the transition frequency or cut-off frequency (f_t), depends on g_m and C_{gs} , C_{gd} . High g_m of CP-BML FET yields in higher f_t than counterpart technology and has been found to be 460 GHz. The frequency characterization FOMs obtained are at par with ITRS performance projections.

Fig. 5 Capacitance (C_{gs} , C_{gd}) in different operating regions for (a) Junctionless BML FET (b) Charge Plasma BML FET.

3.3 Physical Parameter Dependence of FOMs

In this section, the dependence of DC and RF performance metrics on criticality of physical parameters that include L_G , ϕ_{BML} , and t_{Si} are discussed as follows:

Fig. 6 I_D vs V_{GS} at varied L_G for (a) JL-BML FET (b) CP-BML FET.

3.3.1 Criticality of Scaling

L_G scaling traditionally has resulted in devices with faster speed of operation, low dynamic power at the cost of enhanced SCEs that include increased I_{OFF} and DIBL, degradation of SS and V_{Th} fluctuations and roll-off. We have analyzed the scalability performance of the proposed device and compared it with performance FOMs of JL-BML FET at ITRS standard technological nodes. Figure 6(a-b) shows transfer characteristics for JL-BML FET and CP-BML FET for $L_G = 28 \text{nm}$, 22nm, 14nm, 10nm, 7nm. In JL-BML FET, with scaling of L_G from 28nm to 7nm, I_{OFF} current increases from 0.144 pA/ μm to 92.3 pA/ μm yielding an average increase of 4.33 pA/ $\mu\text{m}/\text{nm}$, whereas in CP-BML FET, I_{OFF} current increases from 2.97×10^{-3} pA/ μm to 5.15 pA/ μm leading to an average increase of 0.24 pA/ $\mu\text{m}/\text{nm}$. I_{OFF} mainly breeds from band to band tunneling which in CP-BML FET is minimized by schottky BML which forbids the facilitation of tunneling path to charge carriers in the OFF-state. At $L_G = 7 \text{nm}$, an acceptable $\frac{I_{ON}}{I_{OFF}}$ ratio in accordance to ITRS projections of $\simeq 10^8$ and $\simeq 10^6$ is observed for JL-BML FET and CP-BML FET respectively.

3.3.2 Criticality of ϕ_{BML}

Fig. 7 I_D - V_{GS} at varied ϕ_{BML} for (a) JL-BML FET (b) CP-BML FET.

The critical impact of BML workfunction (ϕ_{BML}) on transfer characteristics of JL-BML FET and CP-BML FET is shown in Fig. 7(a-b) for $L_G = 20\text{nm}$ and $t_{\text{Si}} = 10\text{nm}$. We have analyzed the effect of I_{OFF} for ϕ_{BML} varying from 4.8 eV to 5.2 eV. With increase in the workfunction of BML, the Schottky barrier height increases, creating superior depletion which renders the channel to surface of the device layer, towards the electrostatic influence of gate. The reduction of effective device layer thickness by creating a no free charge carrier region depending on schottky induced depletion limits the OFF-state current as shown. However considering JL-BML FET, the device layer is inherently highly doped (10^{19}cm^{-3}), the barrier height is compromised as compared to moderately doped device layer in CP-BML-FET. One has to be more careful in choosing ϕ_{BML} with JL-BML FET as the OFF-state needs to be achieved by top gate and not merely by schottky induced depletion. The graphical representation of variance of I_{OFF} , I_{ON} is shown in Fig. 9(a-c). At $\phi_{\text{BML}} = 4.8\text{ eV}$ and $\phi_{\text{BML}} = 5.2\text{ eV}$, we have observed I_{OFF} of $1.72 \times 10^{-9}\text{ A}/\mu\text{m}$ and $4.29 \times 10^{-13}\text{ A}/\mu\text{m}$ respectively in JL-BML FET yielding an average decrease of $1.71\text{ nA}/\mu\text{m}/\text{eV}$ while in CP-BML FET I_{OFF} of $2 \times 10^{-12}\text{ A}/\mu\text{m}$ at 4.8 eV and $7.69 \times 10^{-15}\text{ A}/\mu\text{m}$ at 5.2 eV is observed yielding an average decrease in I_{OFF} of $1.99\text{ pA}/\mu\text{m}/\text{eV}$.

3.3.3 Criticality of t_{Si}

The device layer thickness (t_{Si}) is a physical parameter of critical for determination of device characteristics in such kind of architectures. The volume of charge carriers depends on t_{Si} which will ultimately determine the FOMs like I_{OFF} , V_{Th} , and SS. Figure 8(a-b) shows device characteristics for varied t_{Si} for JL-BML FET and CP-BML FET. In JL-BML FET, increasing t_{Si} beyond 10nm leads to increase in I_{OFF} due to inability of high

Table 2 Workfunction of schottky BML for different extent of depletion depths ($y_{\text{dep,BML}}$) for different device layer thickness (t_{Si}) and channel doping concentrations (N_D).

N_D, t_{Si}	$y_{\text{dep,BML}}\%$ age	ϕ_{BML}
$N_D = 10^{19}\text{cm}^{-3}, t_{\text{Si}} = 10\text{nm}$	100% (10nm)	5.88 eV
$N_D = 10^{19}\text{cm}^{-3}, t_{\text{Si}} = 10\text{nm}$	50% (5nm)	5.31 eV
$N_D = 10^{19}\text{cm}^{-3}, t_{\text{Si}} = 10\text{nm}$	20% (2nm)	5.12 eV
$N_D = 10^{19}\text{cm}^{-3}, t_{\text{Si}} = 50\text{nm}$	100% (50nm)	NE
$N_D = 10^{19}\text{cm}^{-3}, t_{\text{Si}} = 50\text{nm}$	50% (25nm)	9.9 eV
$N_D = 10^{19}\text{cm}^{-3}, t_{\text{Si}} = 50\text{nm}$	20% (10nm)	5.88 eV
$N_D = 10^{16}\text{cm}^{-3}, t_{\text{Si}} = 10\text{nm}$	100% (10nm)	4.95 eV
$N_D = 10^{16}\text{cm}^{-3}, t_{\text{Si}} = 10\text{nm}$	50% (5nm)	4.95 eV
$N_D = 10^{16}\text{cm}^{-3}, t_{\text{Si}} = 10\text{nm}$	20% (2nm)	4.9 eV
$N_D = 10^{16}\text{cm}^{-3}, t_{\text{Si}} = 50\text{nm}$	100% (50nm)	4.97 eV
$N_D = 10^{16}\text{cm}^{-3}, t_{\text{Si}} = 50\text{nm}$	50% (25nm)	4.96 eV
$N_D = 10^{16}\text{cm}^{-3}, t_{\text{Si}} = 50\text{nm}$	20% (10nm)	4.95 eV

where, $\phi_{\text{BML}} = \phi_{\text{Si}} + \frac{N_D t_{\text{Si}}^2}{2\epsilon_{\text{Si}}} + \frac{V_T + V_{\text{BML}}}{q}$

workfunction gate to deplete the highly doped channel efficiently. However in CP-BML FET, the channel is moderately intrinsic therefore I_{OFF} is somewhat controlled. It must be noted that selection of ϕ_{BML} and t_{Si} are interdependent and have to be chosen carefully. The dependence of ϕ_{BML} for different depletion depths in JL-BML FET and CP-BML FET with varied t_{Si} is calculated analytically listed in Table 2. It is analyzed that I_{OFF} is significantly affected by t_{Si} and N_D as shown in Fig. 9(c). Since the effective t_{Si} in CP-BML FET depends on λ_D , such doping less architectures FETs are immune to variations in physical parameters as compared to chemically doped devices.

Fig. 8 I_D vs V_{GS} at varied t_{Si} for (a) JL-BML FET (b) CP-BML FET.

3.4 Performance along ITRS Scaling Roadmap Considerations

In this section, different FOMs for JL-BML FET and CP-BML FET are compared for scaling of L_G . A tabular list of all the considered FOMs for different L_G are listed in Table 3. At $L_G = 7\text{nm}$, I_{sat} value of $293\mu\text{A}/\mu\text{m}$ and $975\mu\text{A}/\mu\text{m}$ is observed for JL-BML FET and CP-BML FET respectively which is at par with ITRS 2025 low power requirements. For ultra scaled devices ($L_G = 7\text{nm}$), the JL-BML FET shows V_{Th} roll-off of 100mV while as

Fig. 9 I_{ON} , I_{OFF} variations for different (a) L_G (b) BML workfunction (c) t_{Si} . Insets shows corresponding I_{ON}/I_{OFF} variations.

Table 3 Performance FOMs for JL-BML FET and CP-BML FET for L_g scaling.

Parameter	Junctionless Buried Metal Layer FET Technology Node: Gate Length (nm)					Charge Plasma Buried Metal Layer FET Technology Node: Gate Length (nm)				
	7	10	14	22	28	7	10	14	22	28
$I_{ON}(\mu A/\mu m)$	293	289	287	281	270	975	889	832	750	712
$I_{OFF}(pA/\mu m)$	92.3	20.2	5.94	.313	.144	5.15	.924	.228	6.26×10^{-2}	2.97×10^{-3}
$I_{ON}/I_{OFF}(\times 10^6)$	3	14	48	890	1.87×10^3	189	960	3.6×10^3	1.19×10^5	2.4×10^5
V_{Th} Roll-off (mV)	100	65	40	22	18	80	55	35	20	15
SS (mV/dec)	118	115	110	90	80	108	100	80	75	65
g_m (mS/ μm)	1.59	1.74	1.65	1.54	1.52	2.7	2.66	2.63	2.56	2.53
C_{gs} (fF/ μm)	0.31	0.40	0.52	0.72	0.86	0.38	0.46	0.56	0.75	0.90
C_{gd} (fF/ μm)	0.1137	0.1162	0.118	0.121	0.124	0.109	0.111	0.113	0.113	0.114
f_T (GHz)	560	528	407	290	244	866	739	622	468	396
GBP (GHz)	222	238	222	202	195	394	381	370	360	353
TGF (V^{-1})	5.42	6.02	5.74	5.48	5.62	2.76	2.99	3.16	3.41	3.55
TFP (THz)	3.035	3.178	2.336	1.589	1.371	2.390	2.209	1.965	1.595	1.405
τ (psec)	1.75	2.17	2.69	3.62	4.4	0.6	0.77	0.97	1.3	1.71
P_{dyn} (fJ/ μm)	0.309	0.620	0.86	1.36	1.72	0.248	0.496	0.695	1.09	1.39

Table 4 Comparative analysis of technologies for various FOMs

Device Description	Tech. (L_g)	I_{ON}	$I_{OFF}(\mu A/\mu m)$	$\frac{I_{ON}}{I_{OFF}}$	SS (mV/dec)	τ	P_{dyn} (fJ/ μm)	[Ref]
Charge Plasma SOI FET with BML	20 nm	730 $\mu A/\mu m$	7.69×10^{-9}	10^{11}	75	1.3ps	1.09	[This Work]
Junctionless SOI FET with BML	20 nm	261 $\mu A/\mu m$	1.3×10^{-6}	10^8	90	3.62ps	1.36	[This Work], [20]
Planar Junctionless SOI FET	1 μm	100 $\mu A/\mu m$	50	10^2	150	-	-	[17]
Tunnel Field Effect Transistor	13 nm	10 $\mu A/\mu m$	1 nA/ μm	10^5	60	20ps	ULP	[21]
Negative Capacitance FET	80 nm	1 mA/ μ	10^{-5}	10^8	53.3	10ps	-	[22]
MOS Planar HEMT	50 nm	2.7 A/mm	Normally-On	-	-	0.2ns	High Power	[23]
Planar Schottky Barrier MOSFET	40 nm	0.17 $\mu A/\mu m$	2.1×10^{-3}	10^4	147.87	0.1ns	-	[24]

80mV CP-BML FET is observed in CP-BML FET. V_{Th} roll-off reduces for higher technology nodes indicating the dominance of SCEs for ultra-scaled devices. The SS drops below the thermal limit of 60mV/dec with progressive scaling of L_G but is observed to be more severe in JL-BML FET than the proposed device. The transition or cut-off frequency is given by $f_t = \frac{g_m}{2\pi(C_{gs}+C_{gd})}$. Due to high g_m and lower C_{gs} , C_{gd} in CP-BML FET, f_t of 806 GHz is observed while as f_t of 560 GHz is observed in JL-BML FET. Current gain and unilateral power gain were obtained using s-parameter analysis shown in Fig. 10(a) and (b). The cut-off frequencies were obtained using slope of -20dB/decade.

Gain bandwidth product (GBP) represents the region of operation of FET for which the gain remains constant calculated for DC gain of 10 using $\frac{g_m}{20\pi C_{gd}}$ [25]. Stable high frequency performance is observed in CP-BML FET as compared to JL-BML FET for which the GBP improves with scaling and at $L_g = 7nm$ is found

Fig. 10 (a) Current gain vs frequency (b) Power gain vs frequency.

to be 394 GHz for CP-BML FET. One of the important modern day FOMs for applications like fast mixed signal design include transconductance generation factor ($TGF = g_m/I_{ds}$) and transconductance frequency product ($TFP = TGF \times f_t$). Both FOMs are computed and have been listed in Table 3 for scaled L_g . Two of the major generic FOMs include the intrinsic delay (τ) and dynamic power consumption (P_{dyn}). τ has been computed using $C_{gg}V_{DS}/I_{sat}$. It is found that for ul-

Fig. 11 Dynamic power requirement for different L_G with ITRS trend.

tra scaled CP-BML FET exhibits τ of 0.6 psec which is superior to ITRS projections. τ of 1.71 psec at 28 nm technology node is quite a desired feature as per 2028 ITRS projections. P_{dyn} per W is computed using $C_{\text{ox}}(V_{\text{DS}})^2$ fJ/ μm . ITRS projects that in 2028, P_{dyn} is scaled down to 0.32 fJ/ μm at $L_g=7\text{nm}$. The proposed CP-BML FET yields P_{dyn} of 0.248 fJ/ μm at $L_g=7\text{nm}$ with elevated V_{DD} as shown in Fig. 11. The obtained value of P_{dyn} and τ implicate high performance and ultra low power operation of the proposed device.

Performance comparison with counterpart technologies

Maintaining performance consistency amid downscaling of devices is an unrealistic thing to achieve. In this section we compare some generic technologies with the proposed work shown in Table 4. Tunneling FET is one of the classical approaches to surpass the thermal limit (60mV/dec) of SS at downscaled dimensions of L_g . TFET with $L_g = 13\text{nm}$, has SS of 60mV/dec with improved $I_{\text{ON}}/I_{\text{OFF}}$ ratio with excellent power performance suitable for digital applications however the limited I_{ON} renders the fan-out of the circuit [26]. This problem is the foreground for its wide application particularly at smaller technology nodes. In the recent past, new class of devices with non-classical design approach with steep subthreshold slope device have been proposed called negative capacitance FETs. A device of $L_g = 80\text{ nm}$, has a good ON current, better $I_{\text{ON}}/I_{\text{OFF}}$ ratio with excellent SS of 53.3 mV/dec but suffers from fabrication complexities which involves integration of ferroelectric material in the design [22]. Such FETs have hysteresis effect which increase the intrinsic delay of the device. High electron mobility transistor (HEMT) is cost ineffective normally ON device offering high leakage current and high power consumption limiting its ap-

plicability. Apart from proposed work, all device technologies listed in Table 4 involve chemical doping increasing the thermal budget adjoined by scaling limitation to such technologies. The proposed work involves charge plasma charge carrier induction technique without chemical doping. The device in comparison to other technology devices have high performance and low power requirements. The SS OF 75 mV/dec at $L_g = 20\text{ nm}$ with $I_{\text{ON}}/I_{\text{OFF}} = 10^{11}$ ratio make it competitive candidate for low power requirements particularly at lower technology nodes in accordance to ITRS performance projections. The obtained FMOs indicate at par performance of proposed than complex structured devices enabled with state of the art technologies.

4 Conclusions

Through this work deliver a novel architecture scheme of planar FET design that is significantly advantageous from design, fabrication and performance perspectives. The proposed FET is doping-free transistor with a schotky buried metal layer to induce depletion layer reducing the effective thickness of the device layer. The inclusion of BML in conjunction with charge plasma mechanism reveals a prospective strategy for suppression of SCEs in planar single gate FETs. The proposed FET has been investigated for DC and RF performance FOMs with emphasis on ITRS projections of scaling from 28 nm to 7 nm. The criticality of physical parameter dependence including L_g , T_{Si} , ϕ_{BML} on performance has been investigated in detail. For $L_g = 20\text{ nm}$, and $V_{\text{DS}} = 1.2\text{V}$, the proposed device has superior $\frac{I_{\text{ON}}}{I_{\text{OFF}}}$ ratio of 10^{11} and SS of 75 mV/dec, also I_{ON} and I_{OFF} for CP-BML FET read at $730\mu\text{A}/\mu\text{m}$ and $7 \times 10^{-2}\text{ pA}/\mu\text{m}$ respectively at par with ITRS 2025 performance requirement. With equivalent scaling of L_g from 28 nm to 7nm, I_{OFF} meagerly increased at rate of $0.24\text{ pA}/\mu\text{m}/\text{nm}$ yielding promising results for sub 10 nm technology node. At $L_g=7\text{nm}$, I_{sat} value of $293\mu\text{A}/\mu\text{m}$ and $975\mu\text{A}/\mu\text{m}$ is observed for JL-BML FET and CP-BML FET respectively satisfying ITRS 2025 low power requirements. The power consumption and intrinsic delay performance for 28 nm to 7nm technology nodes are in resonance with ITRS requirements and a desirable diminished trade-off between power and delay is observed in the proposed device. The obtained FOMs of the proposed device make it a potential candidate for low power operations especially with planar single gate architecture FETs.

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Author's Contributions

The main conception of this work is brainchild of N. Shafi (Author 1). A. M. Bhat, J. S. Parmar and A. Powral provided the necessary support regarding simulation and data interpretation. C. Sahu and C. Periasamy supervised the work and made important discussions and modifications to the final manuscript.

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Data Availability

There are no linked research data sets for this submission.

Conflict of interest

The authors declare that they have no conflict of interest.

Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent

Informed consent was obtained from all individual participants included in the study.

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Figures

Figure 1

(a) Conventional bulk planar junctionless SOI FET [17], (b) Bulk planar junctionless with buried metal layer FET, (c) Proposed charge plasma induced dopingless source drain fully depleted buried metal layer planar FET (d) Experimental calibration of simulation model for BP-JLT with [17].

Figure 2

(a). Horizontal energy band variation for JL-BML-SOI FET in OFF and ON state, (b). Horizontal energy band variation for CP-BML-SOI FET in OFF and ON state, (c). Vertical energy band variation in channel for JL-BML-SOI FET in OFF and ON state, (d). Vertical energy band variation in channel for CP-BML-SOI FET in OFF and ON state. OFF state @ $V_{gs} = 0V$, $V_{ds} = 1.2V$, ON state @ $V_{gs} = 1.2V$, $V_{ds} = 1.2V$.

Figure 3

(a) Transfer characteristics for JL-BML FET and CP-BML FET indicating V_{Th} and I_{OFF} at $L_g = 20\text{ nm}$. (b) Transconductance characteristics for JL-BML FET and CP-BML FET at $L_g = 20\text{ nm}$.

Figure 4

Contour diagrams showing electron concentration for (a) JL-BML FET in OFF state, (b) JL-BML FET in ON state, (c) CP-BML FET in OFF state, (d) CP-BML FET in ON state.

Figure 5

Capacitance (C_{gs} , C_{gd}) in different operating regions for (a) Junctionless BML FET (b) Charge Plasma BML FET.

Figure 6

I_D vs V_{GS} at varied LG for (a) JL-BML FET (b) CP-BML FET.

Figure 7

ID-VGS at varied ϕ_{BML} for (a) JL-BML FET (b) CP-BML FET.

Figure 8

ID vs VGS at varied t_{Si} for (a) JL-BML FET (b) CP-BML FET.

Figure 9

I_{ON} , I_{OFF} variations for different (a) LG (b) BML workfunction (c) tSi. Insets shows corresponding I_{ON}/I_{OFF} variation

Figure 10

(a) Current gain vs frequency (b) Power gain vs frequency

Figure 11

Dynamic power requirement for different LG with ITRS trend.