
Alternative Gate Dielectrics for Scaled CMOS Devices

ERC Review
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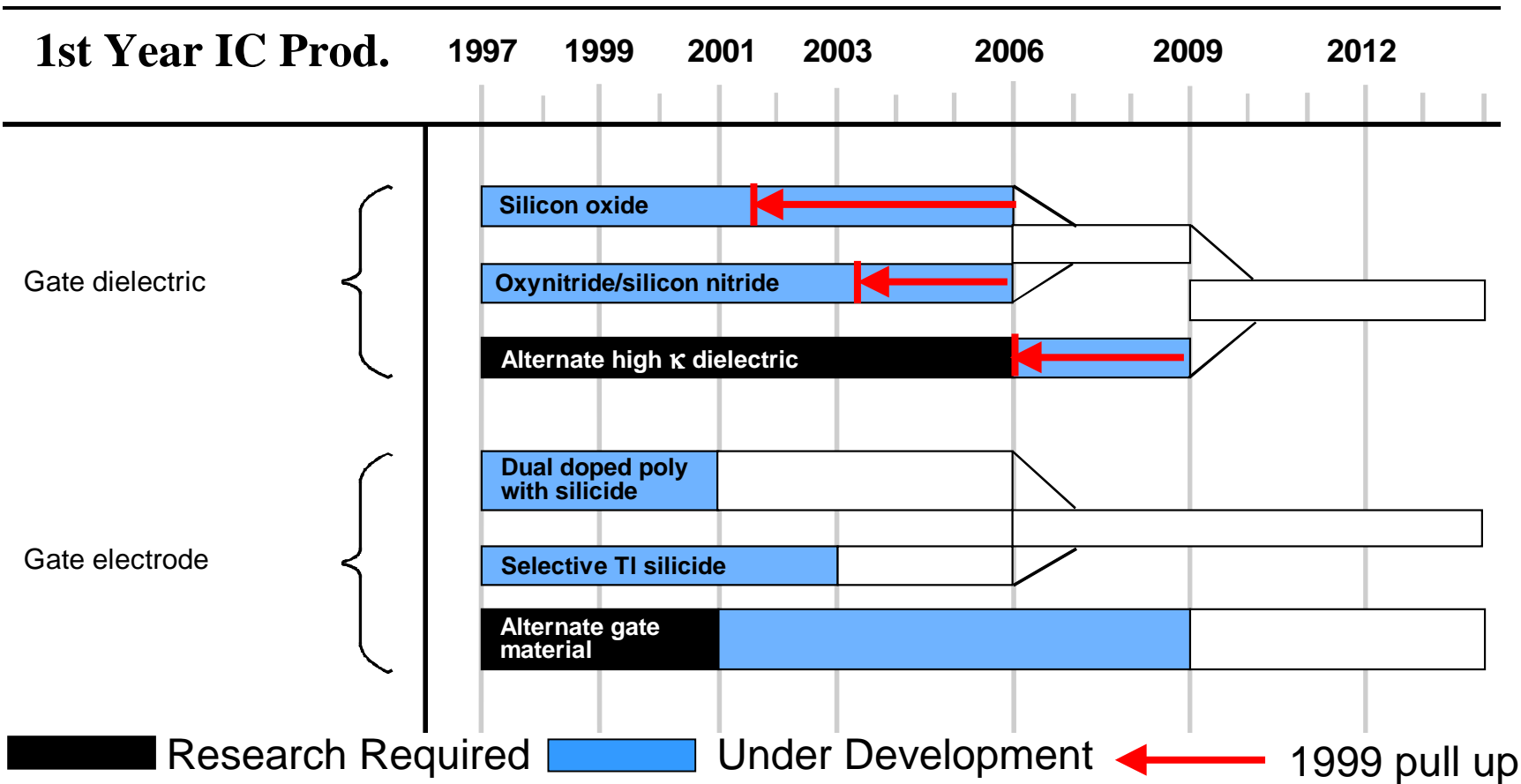
Beyond SiO₂: High-κ Dielectrics

Outline

- **Gate Oxide Scaling - Need to replace SiO₂**
- **Electrical Requirements to replace SiO₂ (High-κ)**
- **Alternate Gate Dielectric Candidates**
- **Future Issues**



IRTS 1997/1999 Roadmap



Semiconductor Industry Association 1997 Roadmap

1999: T_{ox} scaling more aggressive

Table 22 Thermal/Thin Films Gate Etch and Doping Technology Requirements

| Year of First Product Shipment Technology Generation | 1997 250 nm | 1999 180 nm | 2001 150 nm | 2003 130 nm | 2006 100 nm | 2009 70 nm | 2012 50 nm |
|---|----------------|----------------|----------------|----------------|----------------|---------------|---------------|
| Equivalent oxide thickness T_{ox} (nm) | 4-5 | 3-4 | 2-3 | 2-3 | 1.5-2 | < 1.5 | < 1.0 |
| Thickness control (% 3σ) | ± 4 | ± 4 | ± 4 | $\pm 4-6$ | $\pm 4-8$ | $\pm 4-8$ | $\pm 4-8$ |
| Sidewall spacer thickness (nm) | 100-200 | 72-144 | 60-120 | 52-104 | 20-40 | 7.5-15 | 5-10 |



Why is Gate Oxide Thinning Needed?

Higher speed/functionality \Rightarrow higher device density \Rightarrow smaller devices

For transistors: Want High Drive Current $I_D \sim C_{ox}(V_G - V_{th})^2$

Where: $C_{ox} = (\epsilon_{ox}A) / t_{ox}$ $\epsilon = 3.9$ for SiO_2 (dielectric constant)

\Rightarrow Maximize C_{ox} : decrease t_{ox} or increase ϵ

Decrease $t_{ox} \Rightarrow$ gate oxide thinning

For $t_{ox} < 20 \text{ \AA}$

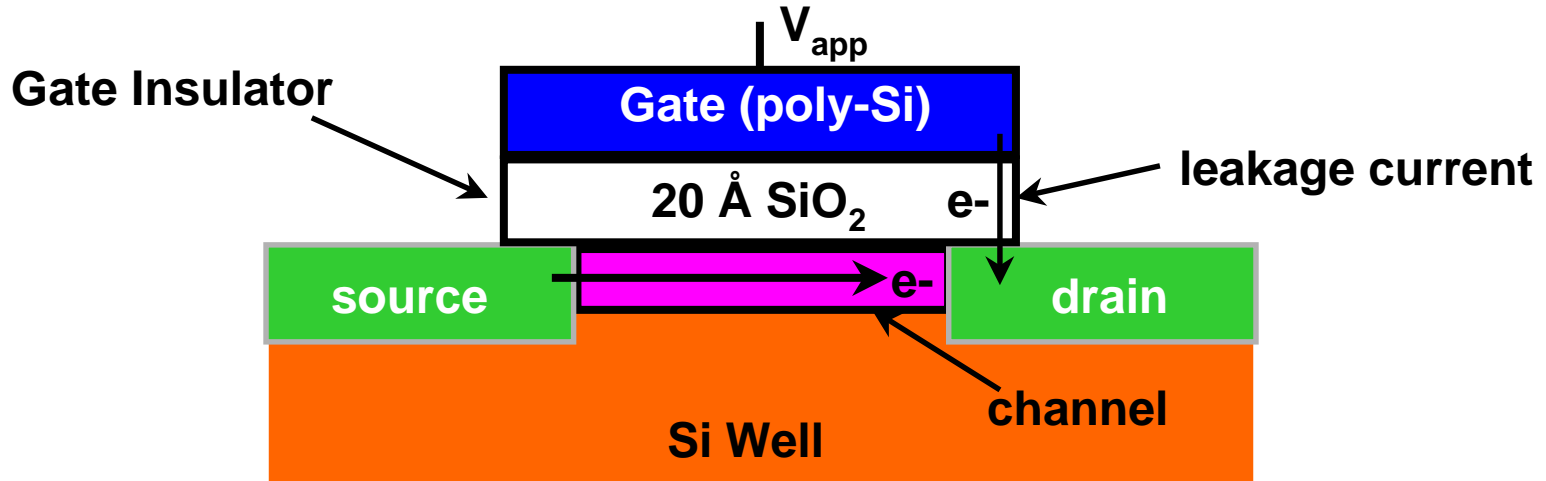
\Rightarrow High leakage (low battery lifetime)

\Rightarrow Boron Penetration

- Increase $\epsilon_{ox} \Rightarrow$ replace SiO_2 with new material
- Or new device design



MOSFET Scaling Gate Dielectric Issues



Problem : Difficult to scale SiO₂ below 14 Å with current manuf.

Solution: Replace SiO₂ with high- κ dielectric to continue scaling

Caution: SiO₂ used as gate dielectric for 40 years - not simple!

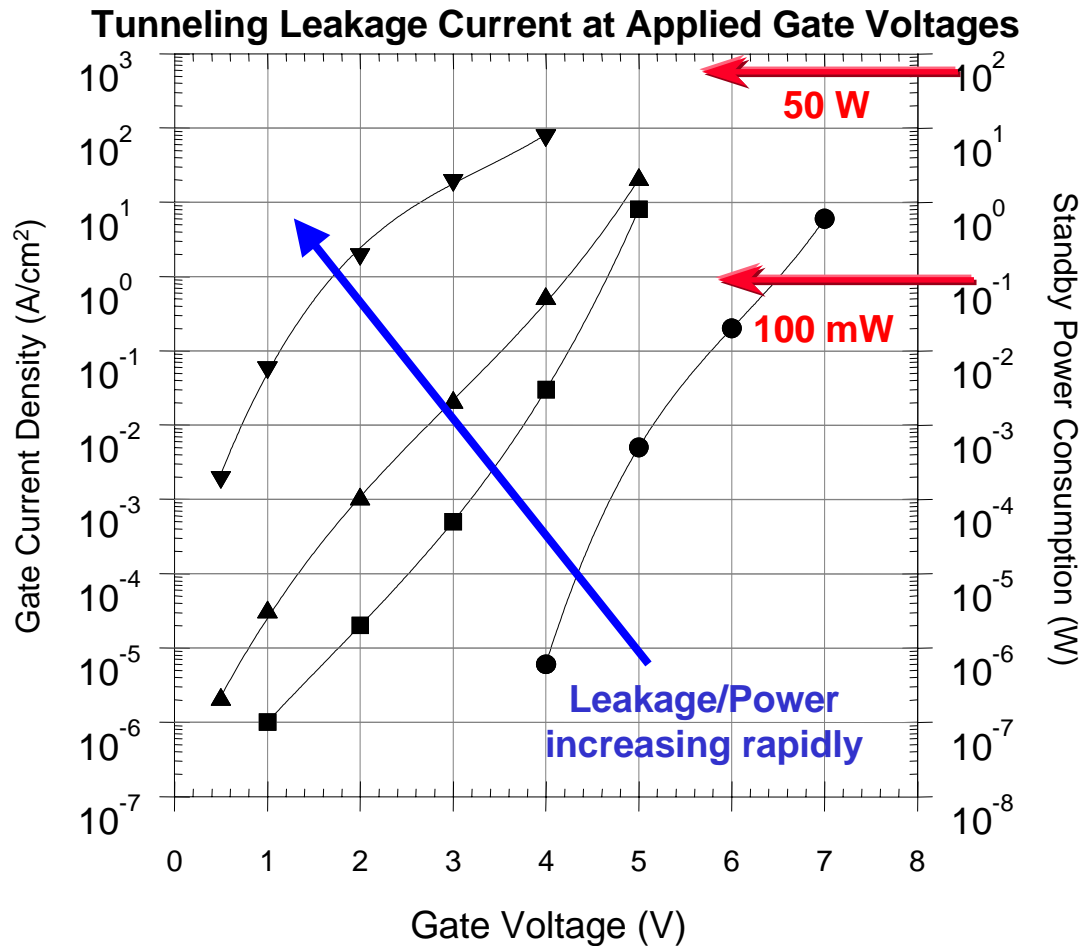


Gate Oxide Thinning: Leakage Current

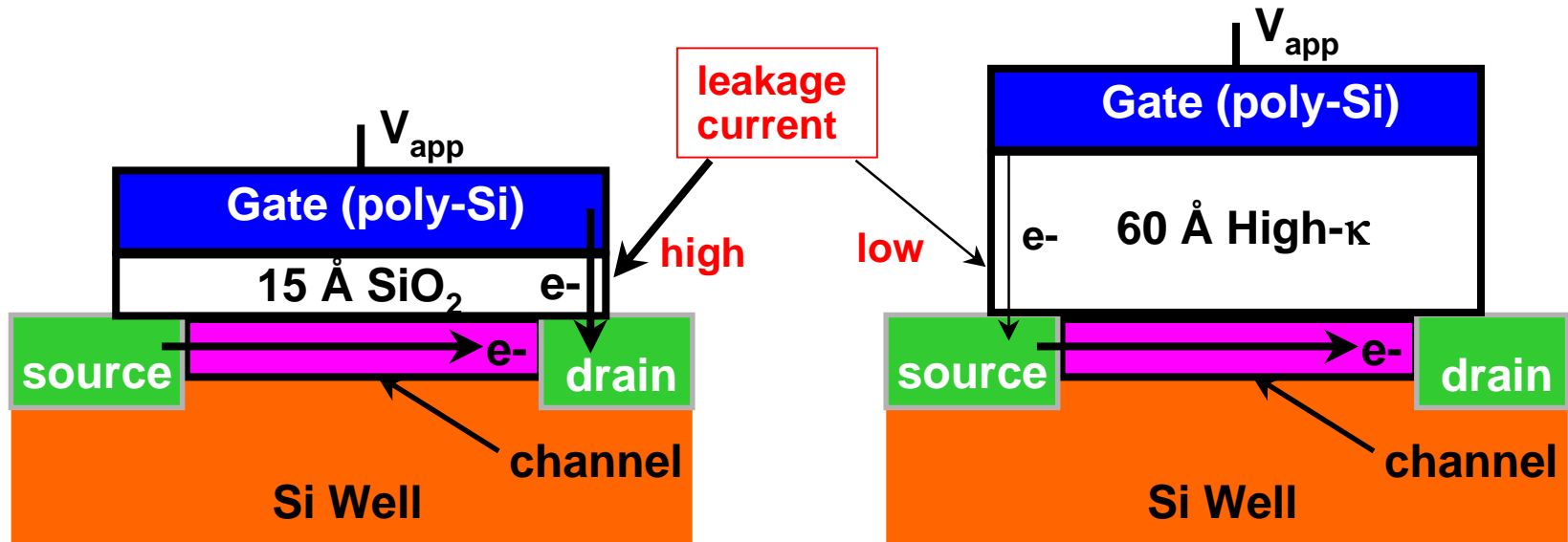
Assumes 0.1 cm² (or less) total gate area

Oxide Thickness

- 5.6 nm
- 3.5 nm
- ▲ 3.0 nm
- ▼ 2.5 nm



High- κ Leakage Reduction



High- κ film \Rightarrow thicker gate dielectric \Rightarrow lower leakage w/ same performance

How to decide which High- κ material is best?



Desirable High- κ Gate Dielectric Properties

Physical Properties

- $\epsilon \sim 15 - 60$
- Band Offset $\Delta E_c \geq 1.5 \text{ eV}$
- Thermally stable next to Si
- Remain amorphous on Si
- Block Boron Diffusion

Electrical Properties

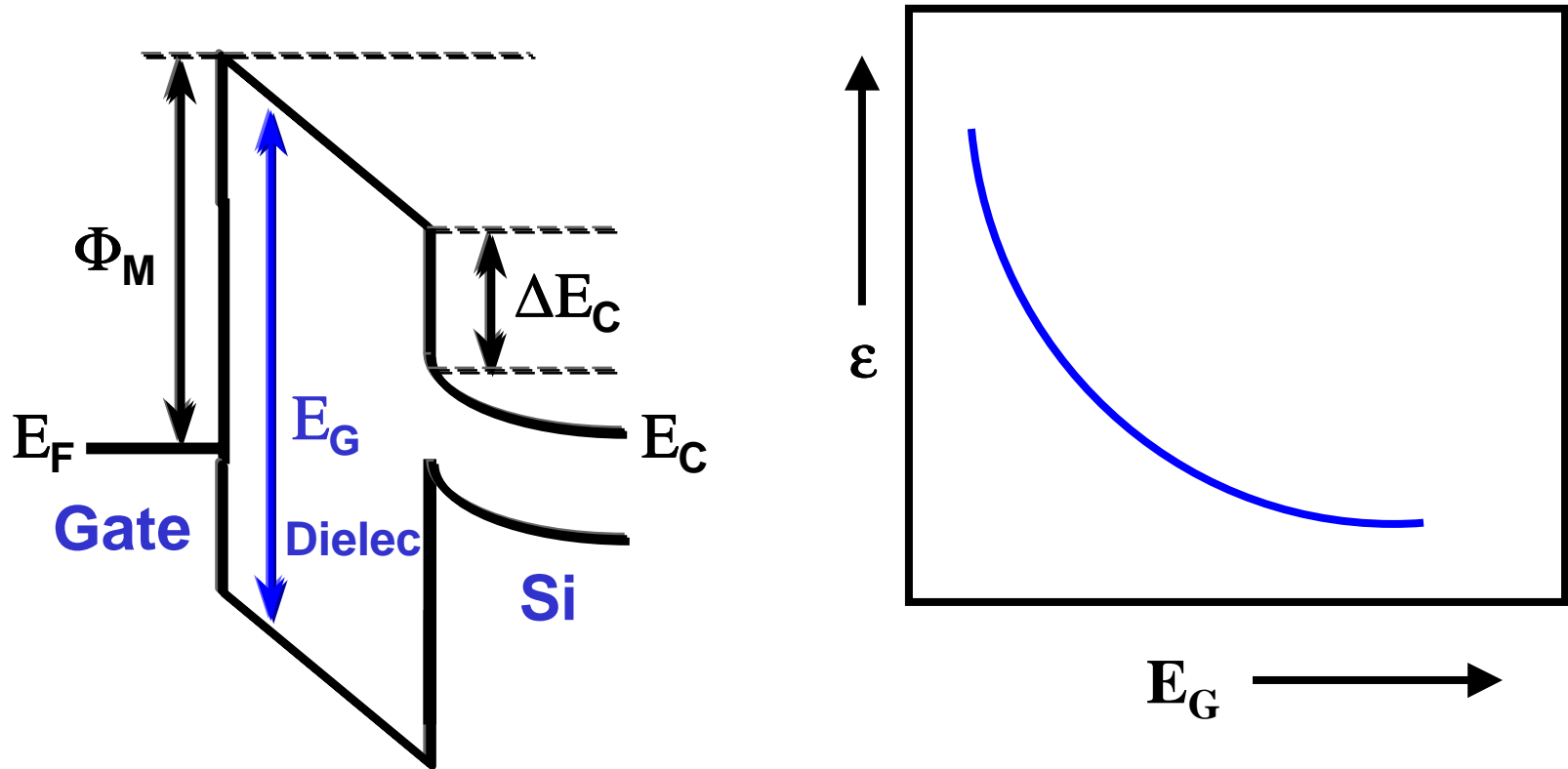
- $t_{\text{ox}} < 10 \text{ \AA}$
- $J < 10^{-3} \text{ A/cm}^2 @ V_{\text{DD}}$
- Minimal dispersion & hysteresis
- High uniformity across wafer
- Reliability as good as SiO_2

t_{ox} : electrically equivalent SiO_2 thickness



Leakage Current: ϵ vs. E_G (and ΔE_C)

Tunneling through Dielectrics



- Leakage current $\sim \exp(-\Delta E_C)$
- Want high E_G , tradeoff with ϵ



Gate Dielectric Properties

| Material | Dielectric Constant (ϵ) | Band Gap E_g (eV) | ΔE_c (eV) to Si | ΔH_F (eV/O atom) | Crystal Structure(s) |
|----------------------------------|------------------------------------|---------------------|-------------------------|--------------------------|----------------------------|
| SiO ₂ | 3.9 | 8.9 | 3.2 | -4.68 | amorphous |
| Si ₃ N ₄ | 7 | 5.1 | 2 | ----- | amorphous |
| Al ₂ O ₃ | 9 | 8.7 | 2.8* | -5.76 | amorphous |
| Y ₂ O ₃ | 15 | 5.6 | 2.3* | -4.93 | cubic |
| CeO ₂ | 26 | 5.5 | (a) | -5.02 | cubic |
| Ta ₂ O ₅ | 26 | 4.5 | 1 - 1.5 | -2.09 | orthorhombic |
| La ₂ O ₃ | 30 | 4.0 | 2.3* | -6.17 | hexagonal, cubic |
| TiO ₂ | 80 | 3.5 | 1.1 | -4.86 | tetrag. (rutile, anatase)* |
| HfO ₂ | 25 | 5.7 | 1.4* | -5.77 | mono., tetrag., cubic* |
| ZrO ₂ | 25 | 7.8 | 1.5* | -5.66 | mono., tetrag., cubic* |
| HfSi _x O _y | 15 - 25 | ~6 | 1.5* | -5.24 | amorphous |
| ZrSi _x O _y | 15 - 25 | ~6 | 1.5* | -5.21 | amorphous |

* J. Robertson Fall MRS 1999

- Si₃N₄, Al and Y-oxides - ϵ too low
- ZrO₂, HfO₂, La₂O₃ good candidates



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- Combine desirable properties from SiO₂ and Al₂O₃ with MO₂, M₂O₃ and M₂O₅ (M = Zr, Hf, Y, La, Ta)
- High- κ M-Si-O and M-Al-O stable & amorphous on Si



High-κ Cation Candidates

(For M_xO_y)

| | |
|-----|-----|
| 8.8 | 8.9 |
| Al | Si |
| 9 | 3.9 |

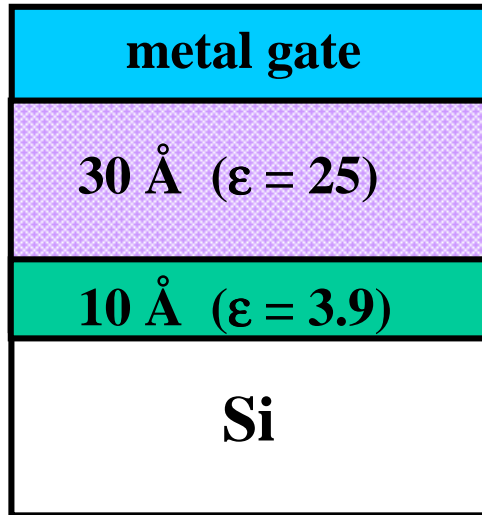
| | | | | | |
|----|------|-------|------|-------|------|
| Ca | Eg → | 3.5 | | III A | IV A |
| | ε → | 80 | Ti | | |
| | | | | | |
| Sr | 5.8 | 7.8 | | | |
| | Y | Zr | | | |
| | 15 | 25 | | | |
| Ba | 5.6 | 5.7 | 4.5 | | |
| | La | Hf | Ta | | |
| | 26 | 25 | 25 | | |
| | II A | III B | IV B | | VB |

For BaSrTiO₃
single crystal films
by MBE only

- Cations most likely to replace SiO₂ gate dielectric
- Combinations of Al or Si with transition metal also possible

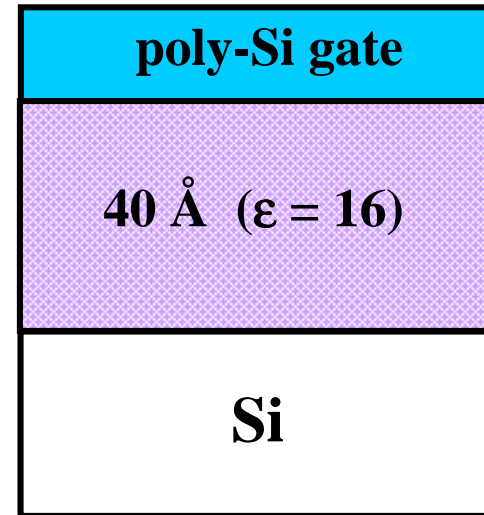


High-κ Stack vs. Single Layer



(1)

$$t_{\text{ox}} = 15 \text{ \AA}$$



(2)

$$t_{\text{ox}} = 10 \text{ \AA}$$

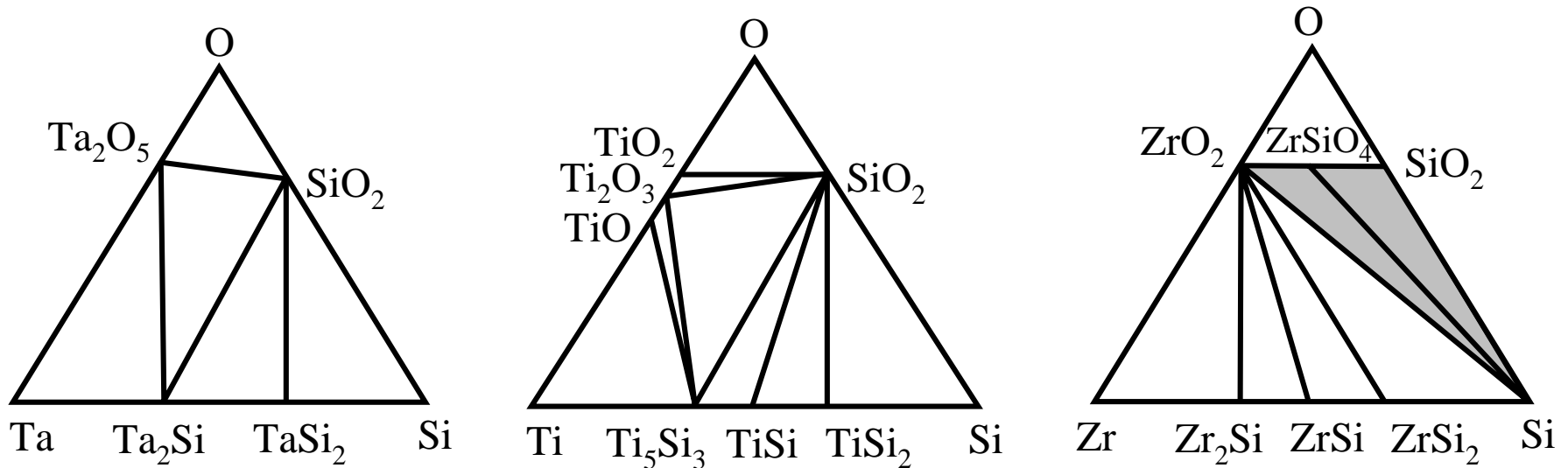
$t_{\text{phys}}(1,2) = 40 \text{ \AA}$, assume same leakage

(2) also retains poly-Si compatibility



Stability of Silicates (700 - 900°C)

After Beyers, J. Appl. Phys. **56**, 147 (1984)
and Wang and Mayer, J. Appl. Phys. **64**, 4711 (1988)

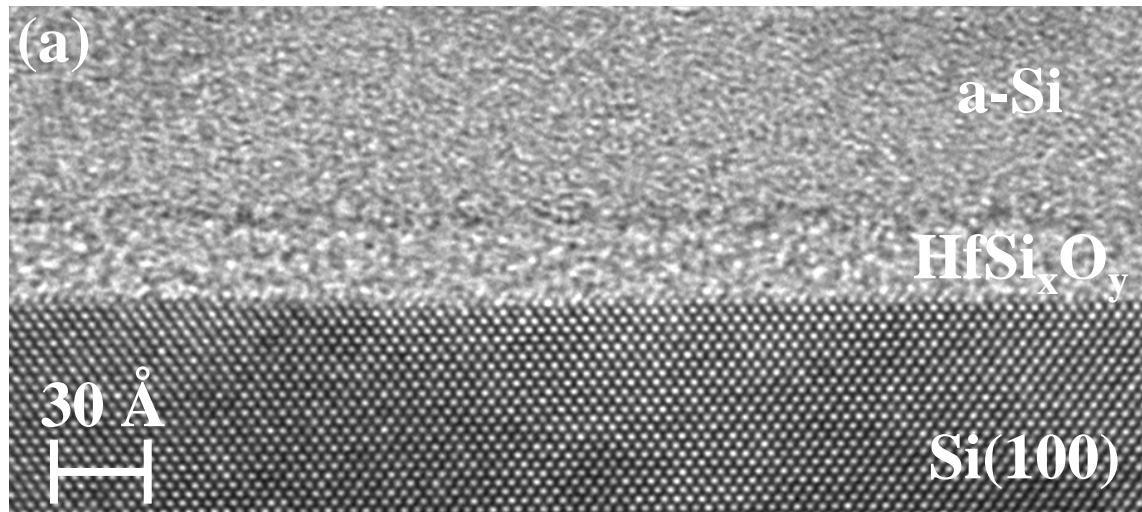


- **ZrO₂/Zr-Si-O stable on Si; Ta and Ti oxide/silicate not stable**
- **Zr, Hf Silicates: no interfacial layer required**

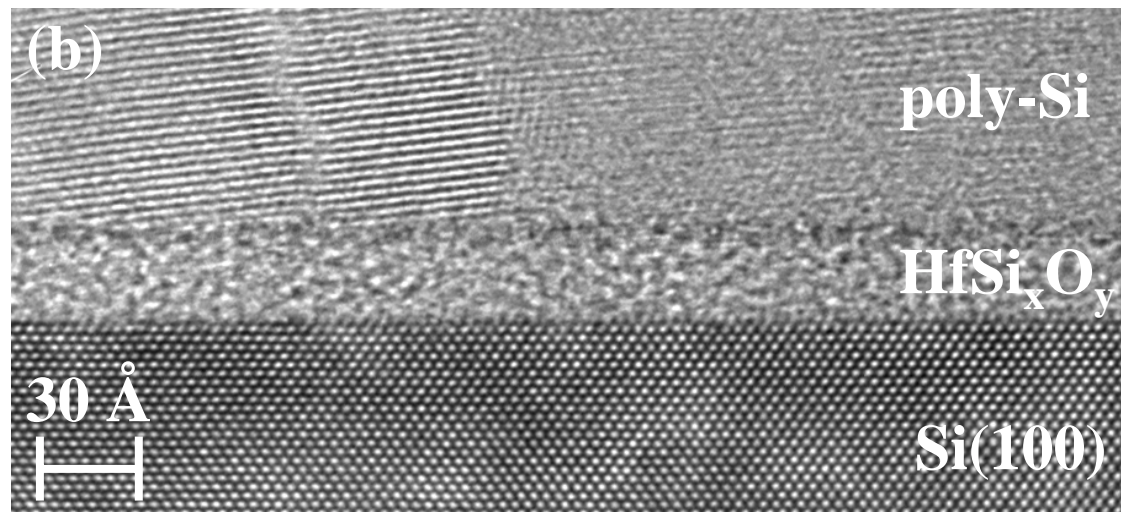


Stability of Silicates on Si: Si cap

As-Deposited
top Si at 25C

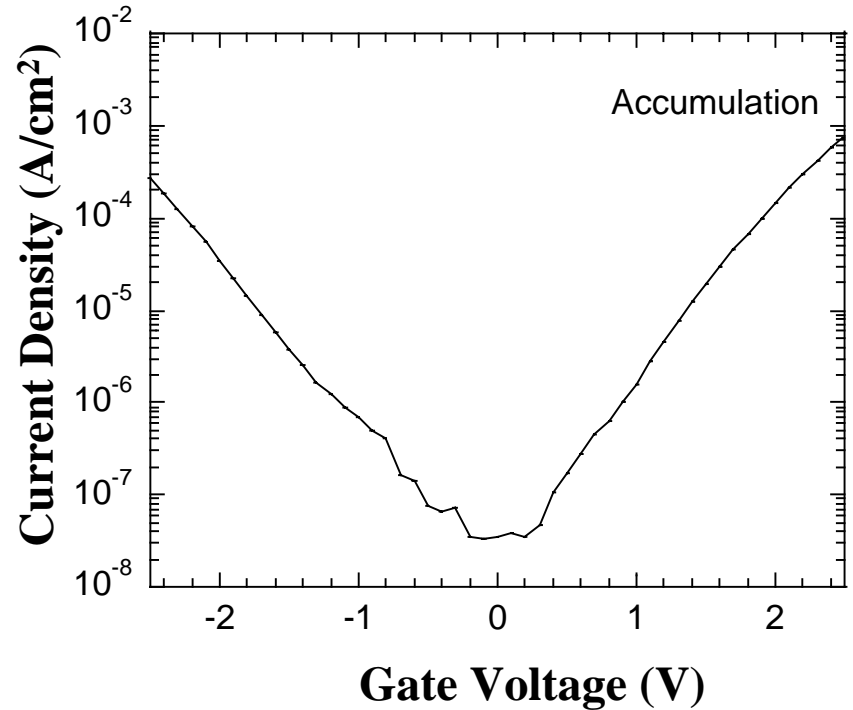
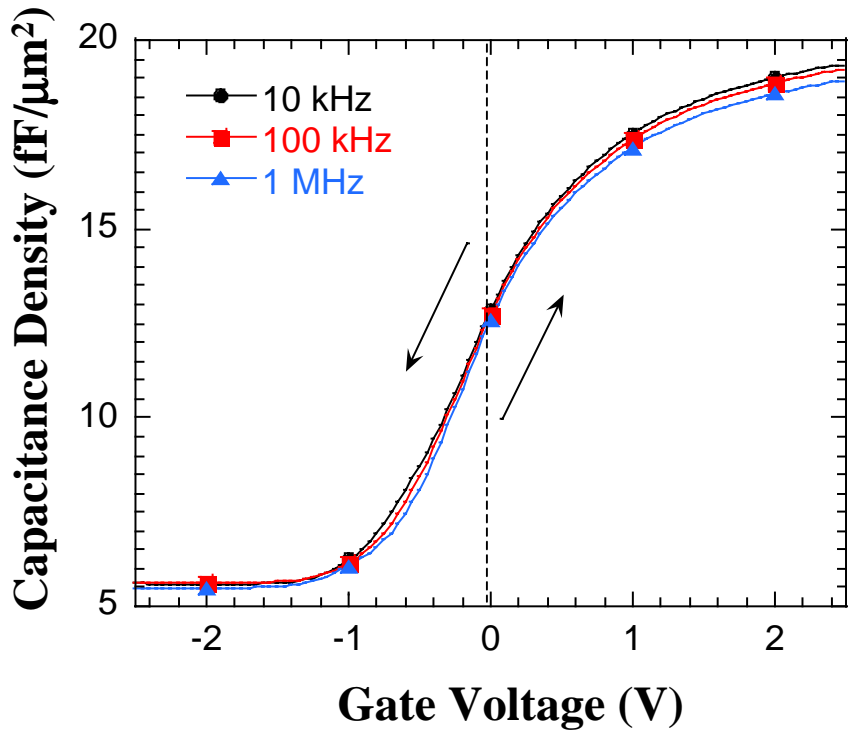


After Anneal
N₂/1050C/20 sec



Silicate Electrical Properties

Au/50 Å (HfO₂)(SiO₂)₅ /n⁺ Si



$$t_{\text{ox}} = 17.9 \text{ \AA} (\epsilon \sim 11)$$

$$J (@1V) = 1.5 \times 10^{-6} \text{ A/cm}^2$$

Hysteresis < 10 mV for silicates

Wilk and Wallace, APL **74**, 2854 (1999)

G. Wilk

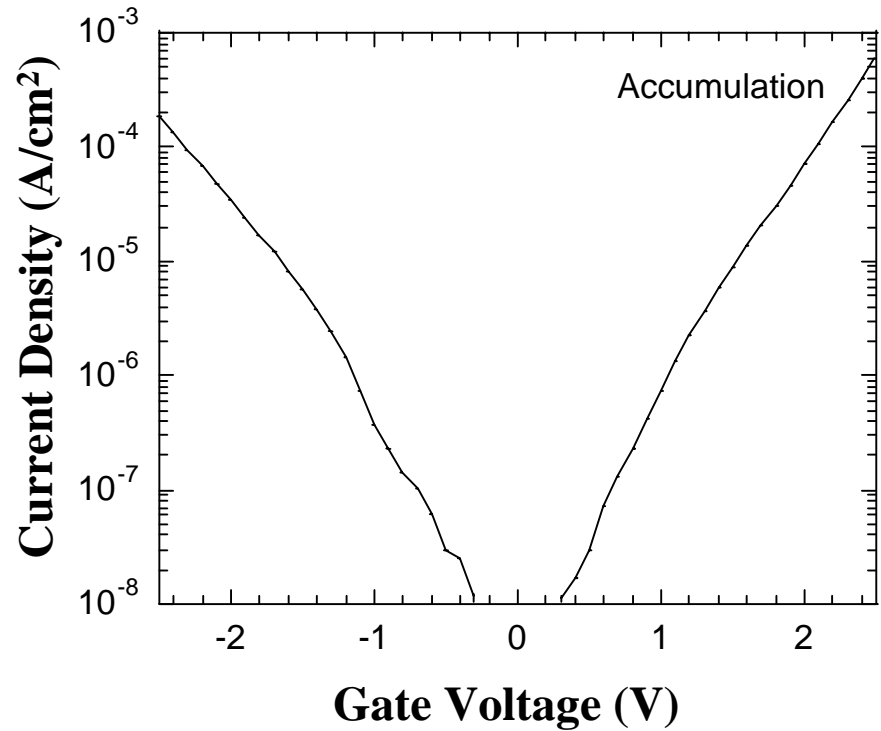
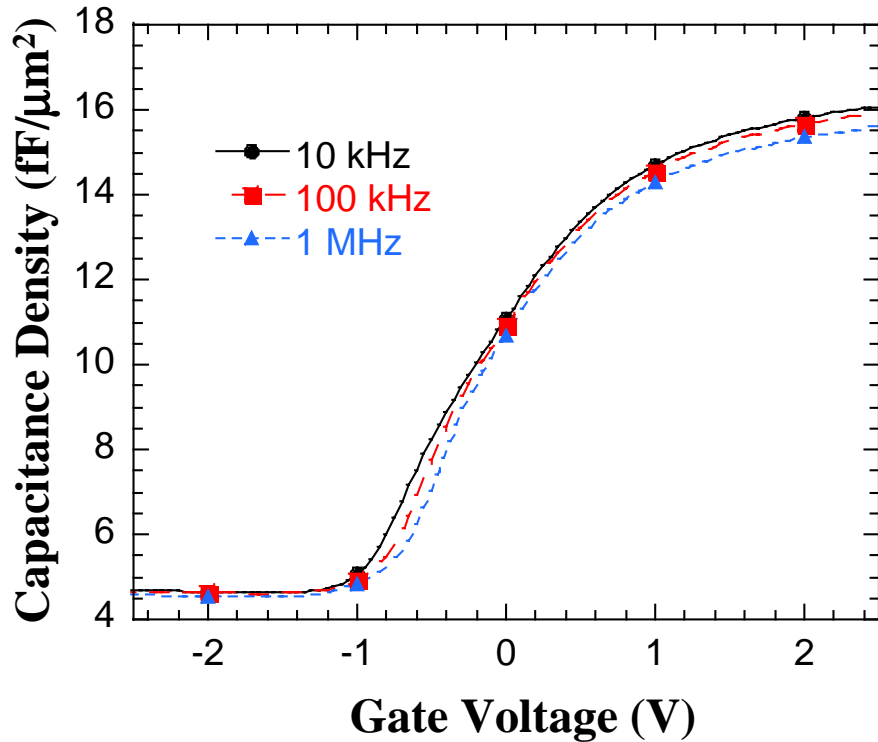
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Lucent Technologies
Bell Labs Innovations



Silicate Capacitor Properties

Au / 50 Å (ZrO₂)(SiO₂)₇ / n⁺ Si

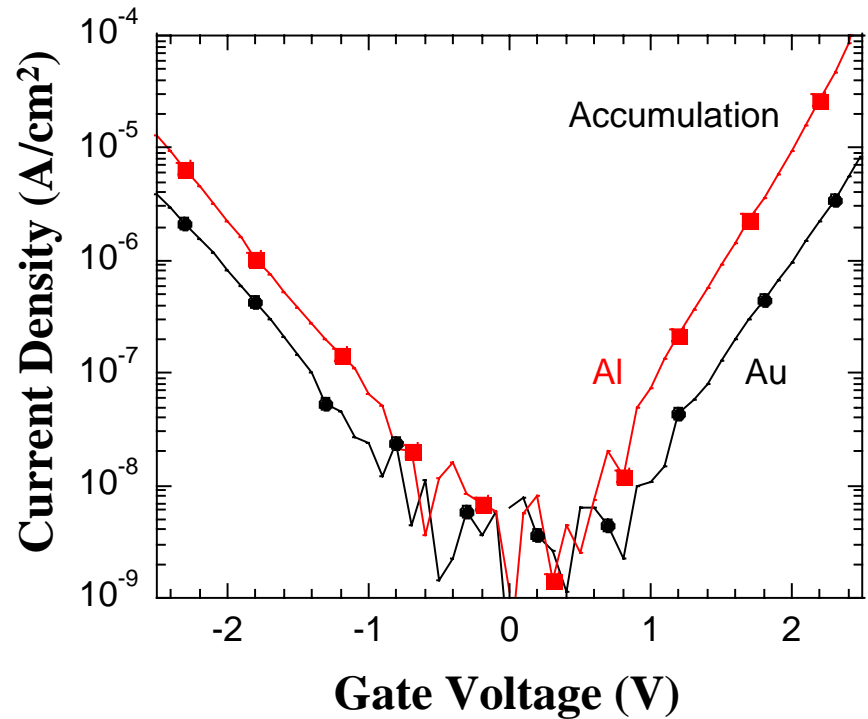
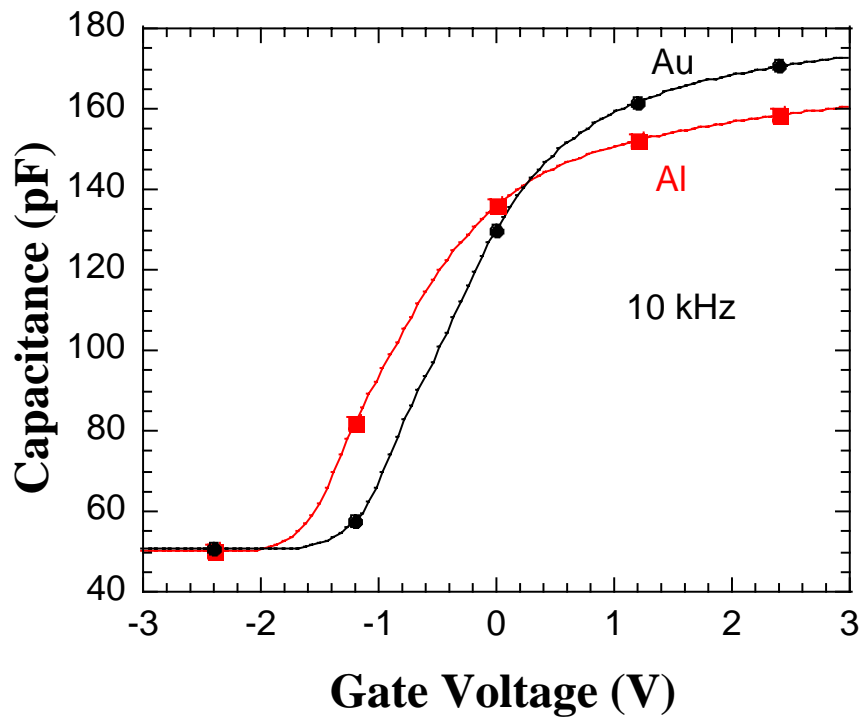


$t_{\text{ox}} = 20.8 \text{ \AA} (\epsilon = 9.4)$

$J (@1V) < 1 \times 10^{-6} \text{ A/cm}^2$



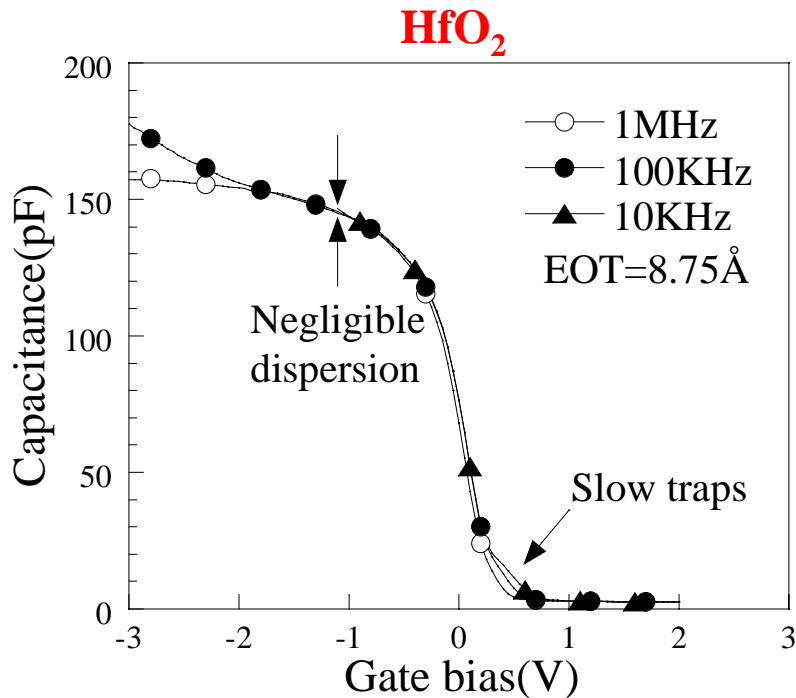
Effect of Electrodes



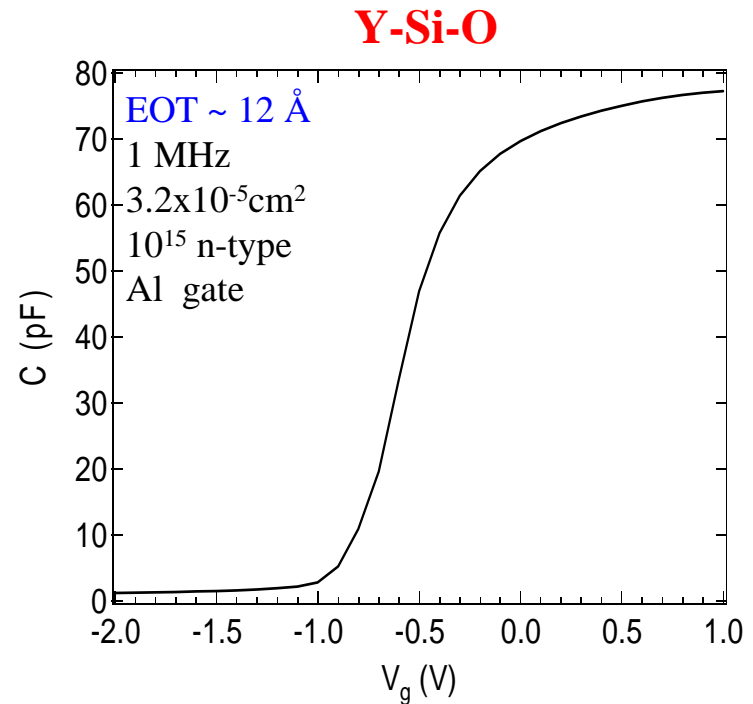
- Au electrodes provide lower leakage in both polarities



Capacitor Properties of HfO₂ and Y Silicate



Frequency dispersion of HfO₂ at -1V <1%/decade.



40Å Y-Si-O film formed by sputter/oxidation of Y on Si(100)

t_{ox} < 10 Å demonstrated with Zr silicate; t_{ox} = 12 Å with Y silicate

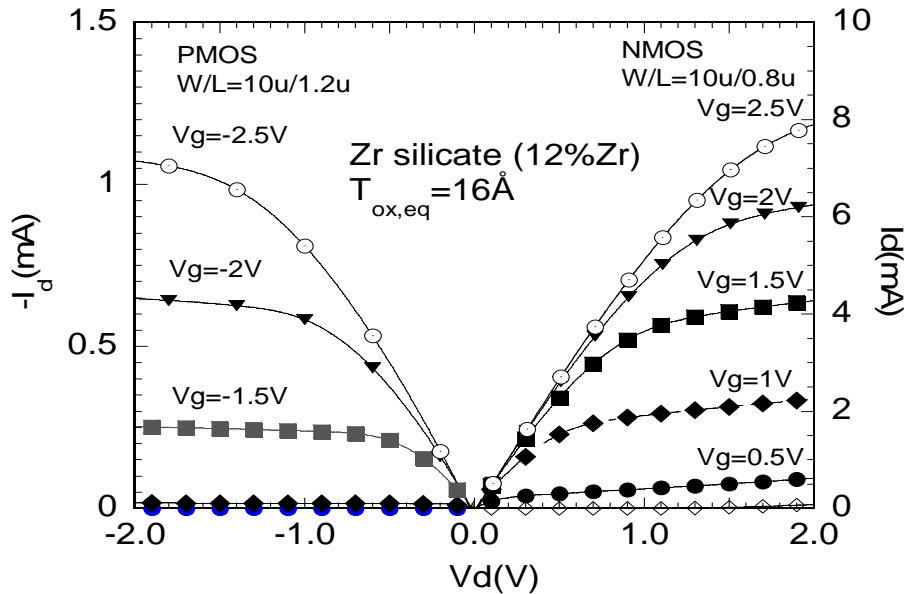
W.J. Qi *et al.*, VLSI Tech. Dig., p. 40 (2000)

Parsons *et al.*, High-κ Workshop
New Orleans, p. 30 (2000)



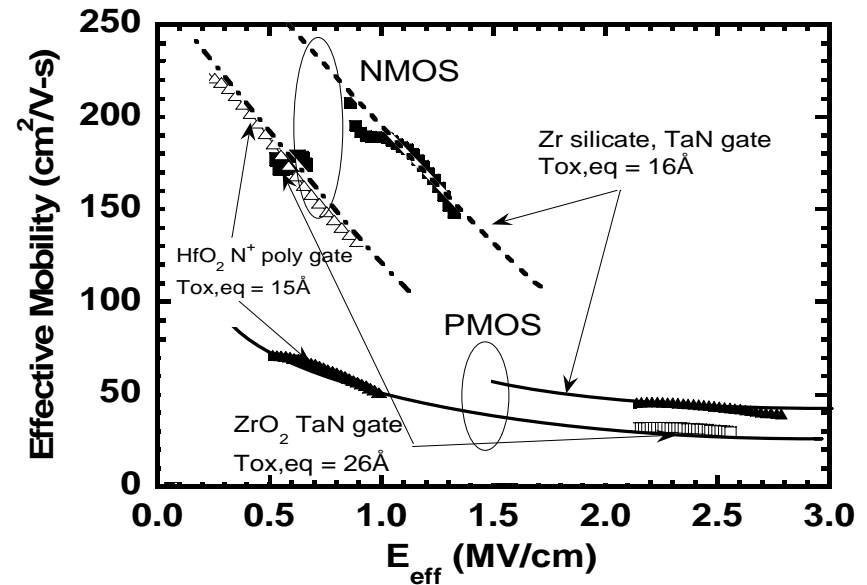
Transistor Properties with Zr Silicate

Zr-Si-O



Id-Vd characteristics of PMOS and NMOS transistors with Zr silicate

Zr-Si-O



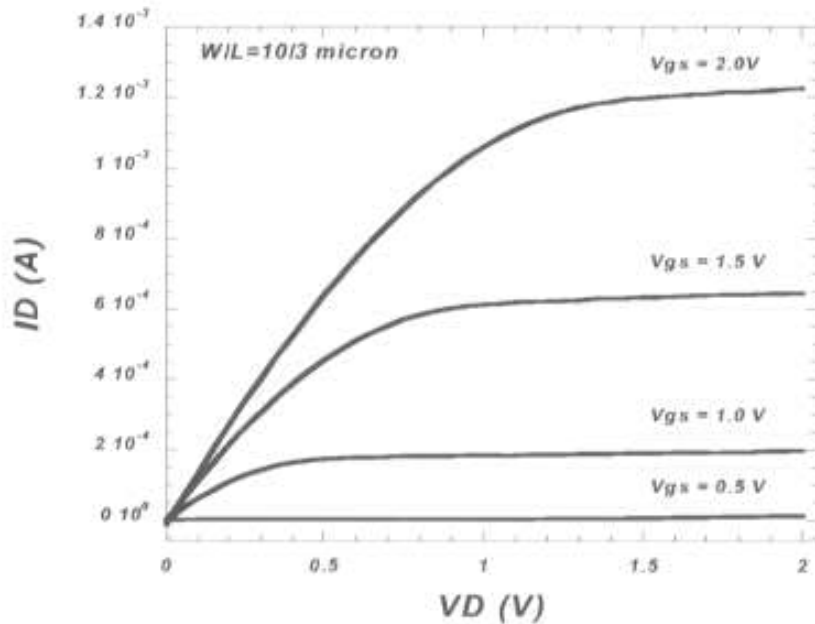
Effective mobility comparison of ZrO₂ and silicate with TaN gate electrode, HfO₂ with n⁺ poly electrode.

W.J. Qi *et al.*, VLSI Tech. Dig., p. 40 (2000)



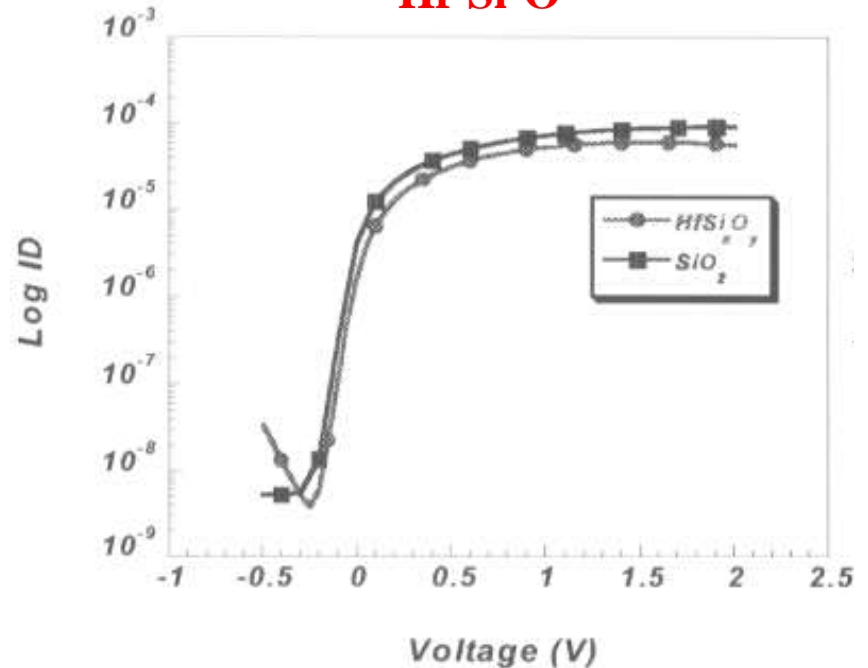
Transistor Properties with Hf Silicate

Hf-Si-O



Id-Vd characteristics of NMOSFET with Hf silicate

Hf-Si-O

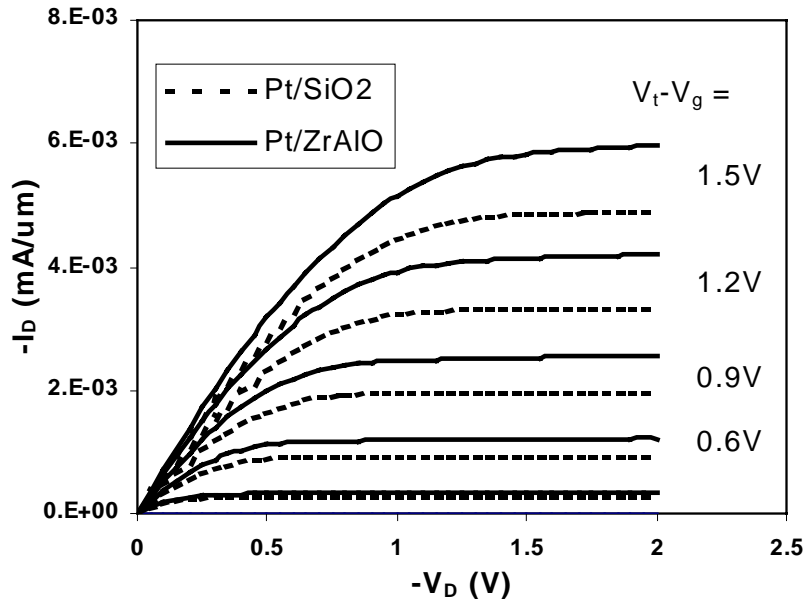


Log Id-Vg of NMOSFET with Hf silicate vs. SiO₂

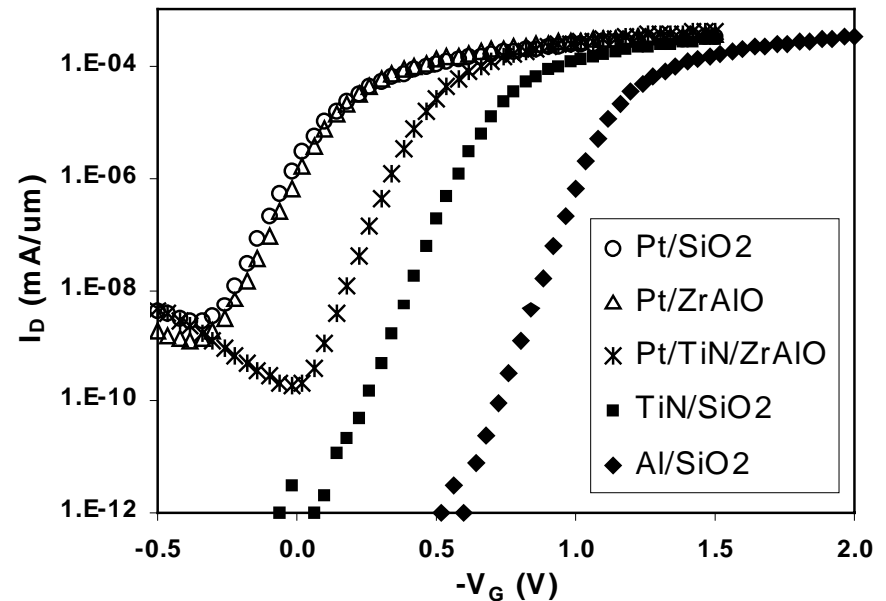
Misra *et al*, High- κ Workshop, New Orleans, p. 36 (2000)



Transistor Properties with Zr Aluminate



Drain characteristics of 10 x 10 μm pMOSFET with Pt gate and Zr-Al-O and SiO₂ dielectrics



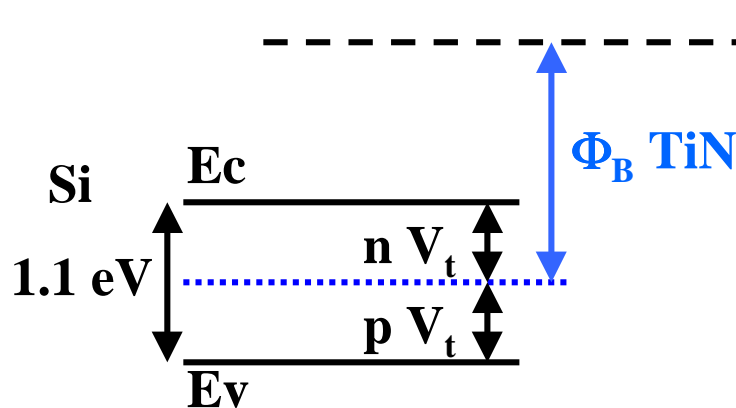
Subthreshold ($V_d = -0.1$ V) of pMOSFET with Al, Pt and TiN gates on Zr-Al-O and SiO₂ dielectrics. Transistor size 10 x 10 μm

Ma *et al*, High- κ Workshop, New Orleans, p. 12 (2000)

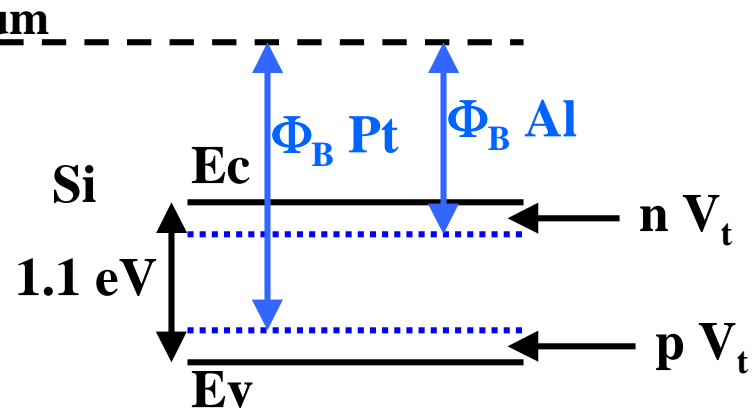


Metal Gate Issues

Single Midgap Metal



Dual Metals



- **Metal gates desirable: eliminate poly depletion and B diffusion**
- **Midgap metals have threshold voltage $V_t \sim 0.5$ eV - too high**
- **Need dual metals to achieve low V_t - which metals?**
- **Ta or TaN suitable for nMOS; RuO_2 or Pt suitable for pMOS**
- **MAY need metals of Ta, Ru or Pt for gate electrodes**



Key Issues for High- κ Gate Dielectrics

- **Interface control**
- **Require $t_{\text{ox}} < 15 \text{ \AA}$, will need $t_{\text{ox}} < 10 \text{ \AA}$**
- **Require $J < 10^{-3} \text{ A/cm}^2$ @ V_{DD}**
- **Thermal Stability**
- **Gate Electrode Choice? Need Compatible materials**



Summary

- **SiO₂ running out of time - need high-κ replacement in 5 years**
- **Metal oxides and alloys most likely candidates**
- **Cations Zr, Hf, Ti, Y, La and Ta most likely in dielectric (Motorola and Oak Ridge pursuing Ba, Sr, Ca, Ti materials)**
- **Metal gates *may* be used, and *may* contain Ta, Pt or Ru**
- **Jury is still out on ALL above materials until more actual devices have been fabricated, tested and optimized**

