The Piezoelectronic Transistor

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The PiezoElectronic Transistor (PET)
Motivation – Overcome CMOS Speed Block

Moore’s Law

• Moore’s Law: transistor density is still increasing

Intel CPU Trends
(sources: Intel, Wikipedia, K. Olukotun)

• But CMOS clock speed has not increased since 2003—limiting processor compute power

• Line voltage $V_{DD}$ has stopped decreasing so power rises unacceptably if speed increases.

• Invent a new type of fast switch with novel physics operable at low voltage/power

• Our PiezoElectronic Transistor (PET) is shown by simulation and theory (based on bulk material properties) to achieve this goal.

Reduce server farm, supercomputer, hand-held device power consumption.
Comparative PET Performance

PET low power, high speed, performance compares favorably with other Switching devices. Fanout supported.

**Power up to factor of 50 saved over the FinFET.**

CNT and TFETs not yet realized.
Piezotronics - Electrical Viewpoint

A *gate* voltage on a *piezoelectric* (PE) applies *pressure* to a *piezoresistive* (PR) material which induces a *insulator→metal transition*, turning on the current through *sense*.

![Diagram of Piezoelectric Transistor (PET)](image)

Straightforward structure for fabrication at industry scales with current litho approaches, but *materials are unconventional* (though well-characterized in bulk).

Jayaraman 1974
The Gate/PE/Common/PR/Sense sandwich is embedded in a high yield strength medium (HYM; e.g., SiN), to hold the Sense-Drive physical distance constant.

The area ratio $\text{Area}_{PR} << \text{Area}_{PE} (a/A)$ steps up the pressure in the PR – the hammer and nail principle.

A void space allows unconstrained motion of the components.
Piezotronics has a *unique* set of advantages:

- Complete technology
- Low power
- Speed – ps time scale
- Low Noise
- **Scalable** – follows Dennard Scaling Law
- High Fan out

IBM’s Bob Dennard
PET Logic and Theoretical Performance
COMPLEMENTARY PETS

For computer circuits need *complementary* PET devices.

One approach is to pole the PE oppositely, generating complementary devices.
Piezotronics can build any logic circuit

Bistable PET Flip-Flop \(\rightarrow\) 4 transistor SRAM

PET inverter

PET NAND gate
PET 1D Modeling to investigate performance

Stress
\[ T(z, t) = c^E \frac{d u(z, t)}{d z} - e^t E(z, t) \]

Surface charge density
\[ \sigma(t) = e \frac{d u(z, t)}{d z} + \varepsilon^S E(z, t) \]

\[ \frac{\partial T(z, t)}{\partial z} = \rho \frac{\partial^2 u(z, t)}{\partial t^2} \]

Impedance of source device

Coupling constant \( g \)
\[ g = \left( c^E d_{33}^2 \right) / \varepsilon^S \]

\( c^E \) = Young's modulus, \( d_{33} \) = Piezo-coefficient nm/volt,
\( e = d_{33} \varepsilon^E \), \( \varepsilon^S \) = dielectric constant at constant strain, \( \rho \) = density
At inverter switch-ON:

- PE displacement transition is underdamped (\(R_{PR}\) provides only damping in model)

- The PE *charges* from source device in \(\tau_{RC}\)

- The PE *expands* in \(\tau_{sonic} = L_{PE} / v_{sound}\)

Ring Oscillator

Chain of inverters plus Feedback loop

Output $V$ of Each Stage (9 stages)

9 stage RO, $V_{dd}=0.076$ V, $R_{ON}/R_{OFF}=5000$, $A/a=25$, $W/L=0.75$, 45 GHz

$L = 26.666$ nm, $W = 20$ nm, $w = 4$ nm, $l = 2$ nm
The Piezoelectronic Transistor at Ultimate Scale

Bruce Elmegreen, based on Kuroda-Martyna multiscale model and measured bulk properties
Materials

PR

PE

SmSe

PMN-PT

SrRuO$_3$

2 nm
Materials are Critical to Achieving PET Performance

**Piezoresistor**

- To get adequate ON/OFF ratio need high PR pressure
- aided by high slope

\[ P_{PR} \approx \frac{d_{33}^{PE} V_G}{l + \left( \frac{a}{A} \right) L} + \frac{Y_{PR}}{Y_{PE}} \]

**Piezoelectric**

- To achieve at low voltage
- need high PE sensitivity \( d_{33}^{PE} \)
- materials operable at small scale \( L, l \)
PR selection – Two Classes of Materials

Rare Earth Intermediate Valence

Mott Transition

\[ \text{Ni}(S_x\text{Se}_{1-x})_2C \]

\[ (v_{1-x}\text{Cr}_x)_2\text{O}_3 \]
SmSe – Pressure controlled Dopant Level

**Rocksalt structure**

SmSe

- **5d**
  - 4f electrons excited into 5d band
  - Pressure promotes 4f electron energy

- **4f**
  - Filled 4f j=5/2 subshell
  - 0.5 eV

- **5d**
  - d band

**SmSe, Hydrostatic Compression**

- **4f** electrons excited into 5d band

**Ab Initio** Modeling shows reduction in 4f-5d gap $E_g$ under stress

- Gap narrowing **greater for anisotropic stress**

- Can fit gap under anisotropic stress to
  
  \[
  E_g = \alpha T_\parallel + \beta T_\perp ; \quad \text{where } T = \text{stress}
  \]

  so gap known in **realistic strain** environment - enabling PET performance prediction
Hot Deposition and Compositional Grading of Sputtered 50 nm SmSe film

XRD superior

Compositional grading for materials development

IV characteristics are close to linear!

AFM scan shows fine-grained polycrystal
Sputtered 50 nm SmTe Films

Novel Microindenter Experiment

- High pressure (GPa range)
- Current flow transverse to film
- Via-confined current flow allows quantitative data analysis
- Pressure vs load calculated by Hertzian mechanics

- 2.5 orders of magnitude resistance change with pressure achieved.
Relaxor PE’s (e.g. PMN-PT) work by polarization rotation

- Near Morphotropic Phase Boundary, polarization can easily rotate from $\langle 111 \rangle$ in the rhombohedral phase towards [001] when the electric field is applied parallel to [001]

- This leads to a large piezoeffect along [001]

\[ \frac{\Delta L}{L} \]

- Starting from tetragonal, there is no polarization rotation along [001], since the polarization is already directed along [001].

**Chemical Solution Deposition of Large Area PMN-PT Films at PSU**

**Polarization vs. Applied Field Hysteresis Loop for PMN-PT films (~350 nm thick)**

- \( P_r = 11 \mu \text{C/cm}^2 \), \( E_c = 33 \text{kV/cm} \), \( \varepsilon_r = 2000 \)
- Dense, columnar microstructure
- \( P_r \) will increase upon imprinting of the P-E loop

![Film surface](image1)

- 500 nm

![Film cross-section](image2)

- 1 \( \mu \text{m} \)

- High quality films now on 8” substrates
- Adequate piezoelectric coefficients / high fields achievable for test devices
- S. Trolier-McKinstry et al, Penn State
Chemical Solution Deposition of Large Area PMN-PT Films at PSU

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Dielectric Constant

Conclusions:

- Estimated effective dielectric constant in experiments (PSU) fall between expected values for $x=0.30$ and $x=0.33$ single crystals.

- Increase of effective dielectric constant with reduction of antenna width not as rapid as ideally model, suggesting small degradation of piezoelectric response after etching.
Improving PE Materials

Textured PZT → Epitaxial PMN-PT → Single Xtal PMN-PT

PZT for Gen-1

\[ \text{\(d_{33}\)} \text{ (pm/V)} \quad 170 \]

\[ \text{\(d_{33}\)} \text{ (pm/V)} \quad 600 \text{ 2x more expected} \]

\[ \text{\(d_{33}\)} \text{ (pm/V)} \quad 2820 \]

C.B. Eom et al.
Devices
Piezotronic Development Plan

Materials

Device Test Structures

Integrated Devices and Circuits

Goal: Demonstrate a fast, low-power device to take digital electronics beyond the voltage-scaling limits of the field-effect transistor.

Phase 1

Phase 2

Phase 3
Split Actuator – Sensor Design for Gen-1 PET

Processed Sapphire wafer

Sensor Pillar

Pillars Randomly Aligned to Actuator
• Engineering choice of process and materials relies heavily on Gen-1 learning.
• Preliminary experiments done to investigate compatibility issues.
Possible Impediments to Scaling

- Fundamental physics of relaxor piezos like PMN-PT – Theoretical research needed
- Practical limits on $d_{33}$ at small scales $\sim 30$ nm – not known - Experimental research needed
- Dead layer at PE/metal boundary – controllable by materials
- Minimum resistivity will limit RC time constant at small areas - OK for SmSe ultimate designs
- Minimum thickness $\sim 3$ nm - controlled by onset of tunneling – Needs experimental check
- Minimum width $w$, depends on lithography – sublithographic shapes possible
- Dead layer on surfaces (e.g. due to oxidation) or need for protective sidewall may limit the mechanical mobility of small PR pillars– test and explore solutions