THz-transistors:

Mobile/(broadband) wireless communications is changing everything. Portable communication devices like the cell phone, along with 3G, WLAN, Bluetooth® are spurring the demand for high frequency, mixed signal integrated circuits that are inexpensive, reliable and have a long battery life. CMOS technology can satisfy these demands. The relentless scaling of CMOS toward nanometer-scale gate lengths has produced MOSFETs with digital and RF performance that is suitable for mixed-signal applications.

The merit of a transistor depends on the circuit design. While large signal digital integrated circuits often use gate delay as a metric, the same loading conditions don't generally apply to RF circuits. Three (metrics)/figures-of-merit appropriate to small-signal RF performance are the cut-off frequency associated with the short-circuit current gain,

$$f_T \approx g_m / 2\pi(C_{gs} + C_{gd}) \quad \sim 1/L_g^n \qquad (1)$$

the maximum frequency of oscillation (where the unilateral power gain vanishes),

$$f_{\max} \approx f_T / 2\sqrt{R_g(g_{ds} + 2\pi f_T C_{gd})} \sim 1/\left(L_g^n W\right) \quad (2)$$

and the noise figure F_{min},

$$F_{\min} \approx 1 + Kf\sqrt{g_m(R_g + R_s)} / f_T \qquad (3)$$

where g_m is the transconductance, C_{gs} and C_{gd} are the gate-to-source and gate-to-drain capacitances, R_s is the parasitic source resistance, R_g is the (lumped) gate resistance, g_{ds} is the output conductance, W is the total gate width, n is an index that ranges from $1<n<2$ depending on the transistor model (short or long channel), and K is a constant that depends on the technology. Ostensibly, improvements in f_T follow from scaling of the gate length, L_g. There has been a progressive increase in f_T to 330GHz for a 60nm gate length nMOSFET, which is comparable to observations in sub-100nm InP HEMTs, but still inferior to reports on *SiGe* and InP/InGaAs HBTs. On the other hand, in MOS technology, f_{max} generally lags behind f_T — the disparity can be accounted for by parasitics, such as R_g and g_{ds} that are not optimized in a core CMOS manufacturing process. With acceptable gain, the noise figure, F_{min}, also has to be minimized to make effective use of CMOS technology for RF. Like f_T, F_{min} has been found to improve (diminish) with each technology generation, but just like f_{max}, F_{min} also depends on parasitic elements that are sensitive to the gate bias and geometry.

Along with the RF performance, another prerequisite for the implementation of mixed circuits in CMOS is accurate, high frequency models for the MOSFET[13-24] and passives. Specifically, the MOSFET model must accurately represent the power gain, input and output impedance and phase delay between the gate voltage and the drain current. A microwave table-based approach to modeling can be very accurate, but requires a large database obtained from numerous measurements and computationally intensive simulations—it becomes intractable for designing highly integrated CMOS communications circuits. Instead, a compact physics-based model is preferred, but a physics-based model has to be valid over a range of bias conditions, temperatures, and frequencies. Consequently, it has to account, not only for parasitic resistances and capacitances, but also for non-quasi-static (NQS) or distributed effects in the gate, substrate and channel resistances due to the channel propagation delay, and non-reciprocal capacitances that account for the different effect of the gate and drain on each other in terms of charging currents.

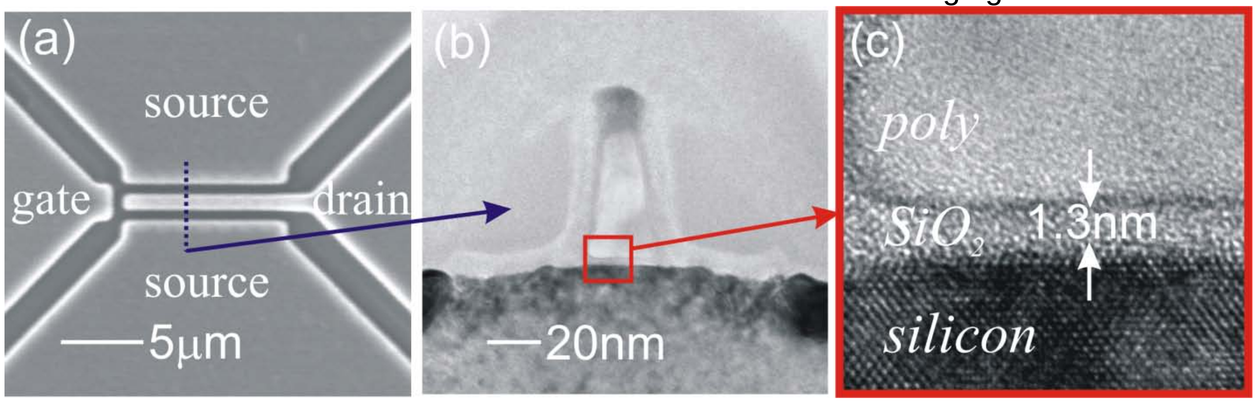

Figure 1. (a) A scanning electron micrograph of a MOSFET tester (metal contacts to the Source, Gate, and Drain shown here). The cross section of the MOSFET (blue dashed line) is shown in Fig. (b). **(b)** A transmission electron micrograph of one finger of a nominally 30nm gate length nMOSFET with a 1.3nm thick gate oxide. The gate is comprised of heavily doped polysilicon 95nm thick with a $CoSi_2$ strap. The 40nm sidewalls consist of a 10nm thick oxide beneath 30nm of silicon nitride. A magnified view of the area outlined in red is shown in Fig. **(c)**. The gate oxide in appears to be about 1.3nm thick.

As illustrated in Figure 1, we have fabricated, tested and modeled of the RF performance of sub-50nm gate length nMOSFETs to assess their suitability for mixed signal applications in the super high frequency (SHF) band, i.e. 3-30GHz. Using a conventional process flow suitable for a digital technology, we fabricated *n*MOSFETs with gate lengths as short as 30nm, and then we measured the DC and RF performance. Following Rashkin we extended the usual de-embedding methodology[29] to account for additional access capacitances associated with metal interconnections running between the (SOLT) reference plane and the contacts to the drain, source and gate. With this refinement, we extracted an f_T =0.465 THz from measurements of a 30nmx40μmx2(finger) *n*MOSFET taken in the frequency range 1GHz<f<50GHz at V_{ds}=2V, V_g=0.67. *This is the highest cut-off frequency reported for a MOSFET so far.* It represents a substantial improvement over previous extrapolations using the same transistors (f_T =0.29 THz) that do not account for the access capacitance. However, our measurements of f_{max}≤0.14 THz and noise figure F_{min}=0.9dB at 8GHz indicate that parasitics still impose limitations on SHF operation. The equivalent circuit that we developed to model the RF performance is based on Tsividis's work incorporating the effect of extrinsic and access parasitics and NQS. This model gives an accurate accounting of the measurements of the *Y* parameters in the frequency range from 1 to 50GHz and scales appropriately with the transistor layout.

Nanotechnology like this offers an interface for harnessing biology to inorganic materials for applications ranging from medicine to biocomputing to chemical process engineering. But to effectively harness biology, we must first understand the dynamic forces and molecular components comprising the interface between biologicals such as proteins, lipid layers, DNA—the constituents of a cell—and the nanostructure of an inorganic surface. These forces depend on electrostatics, biophysical-chemical and Van der Waals interactions, and the like, and they affect how a molecule functions. For example, the chemistry associated with a protein is intimately related to its conformation, and so forces that change the conformation can affect enzymatic activity and specificity. Understanding the nano-bio interface can be accomplished through analysis by imaging and spectroscopy, but conventional techniques are deficient. X-ray crystallography lacks the ability to monitor the large (nanometer-scale) amplitude motions associated with biological functions, and techniques like neutron scattering provide only limited resolution and represent an ensemble average; they cannot image an individual molecule. On the other hand, STM, coupled with THz excitation, is an ideal modality for inducing large amplitude molecular motions in a single molecule and analyzing them—it represents the ultimate in sensitivity and tests the dynamics.

What makes the prospects for molecular imaging and spectroscopy especially bright is the recent discovery that large macromolecules like proteins and *DNA* have distinctive spectral signatures at 0.3-10 THz related to large amplitude vibrational and even functional modes, such as in the activation of a binding site of an enzyme by a hinge motion. Terahertz radiation spans frequencies from 0.1 THz< f <10 THz (or wavelengths from 3mm > λ > 30μm). It can penetrate deep (cm) into many organic materials without the concomitant damage associated with ionizing radiation. THz is absorbed by water, so it can be used to discriminate between materials with different water content like muscle and fat. Yet substrates such as paper, plastic, textiles, and even semiconductors are essentially transparent to them. Thus, leveraging biochemical spectral signatures with deep penetration should allow us to resolve at the molecular level the functional aspects of three dimensional nanosystems such as living tissue without the need for contrast agents or tags. But until now, it has been difficult to exploit the THz part of the spectrum because it lies in the gap between microwave electronics and IR optics. The carrier velocity limits transistor performance above 100GHz, and even though quantum-cascade lasers (QCL) have been demonstrated in the THz band with ~100mW peak power, they work best at <100K—room temperature operation has remained elusive so far.

Currently, we are trying to construct a THz-Imaging Spectrometer and test it on various prototypical single molecules. The spectrometer is based on principles we developed to study single molecule infrared (IR) absorption with sub-molecular spatial resolution, independent of wavelength or focusing. As illustrated schematically in Figure 2, a THz beam emanating from a bright compact transistorized THz source will be transmitted through a wedge to the front surface of a substrate, where the radiation is totally, internally reflected. The evanescent THz wave penetrates above the surface, fully illuminating any macromolecule immersed in electrolyte there, immobilized by target-specific linker chemistries. Resonant THz radiation drives functional and vibrational motion in the molecule. By frequency-modulating the THz beam between a resonant and a non-resonant wavelength, the molecular motion is modulated, resulting in a change of the local electronic density of states associated with the molecule that is detected by an STM tip. Although the THz beam illuminates an area of ~1 mm^2 with long wavelength (sub-mm) THz radiation, the motion of a single molecule is detected with sub-nanometer resolution by the STM. Besides providing a modulated tunneling current, the STM tip enhances the THz electric field ~1000x, increasing sensitivity.

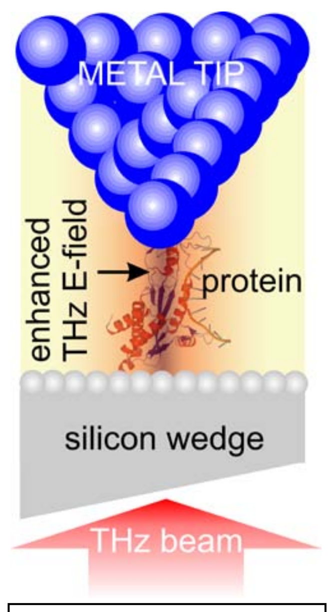

FIGURE 2. A THz evanescent wave propagates into a wedge, where it excites a biomolecule. The resulting change in structure is scanned with sub-nm resolution by an STM tip.