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Diffusion Model of Nonlinear HPM Effects in Advanced Electronics

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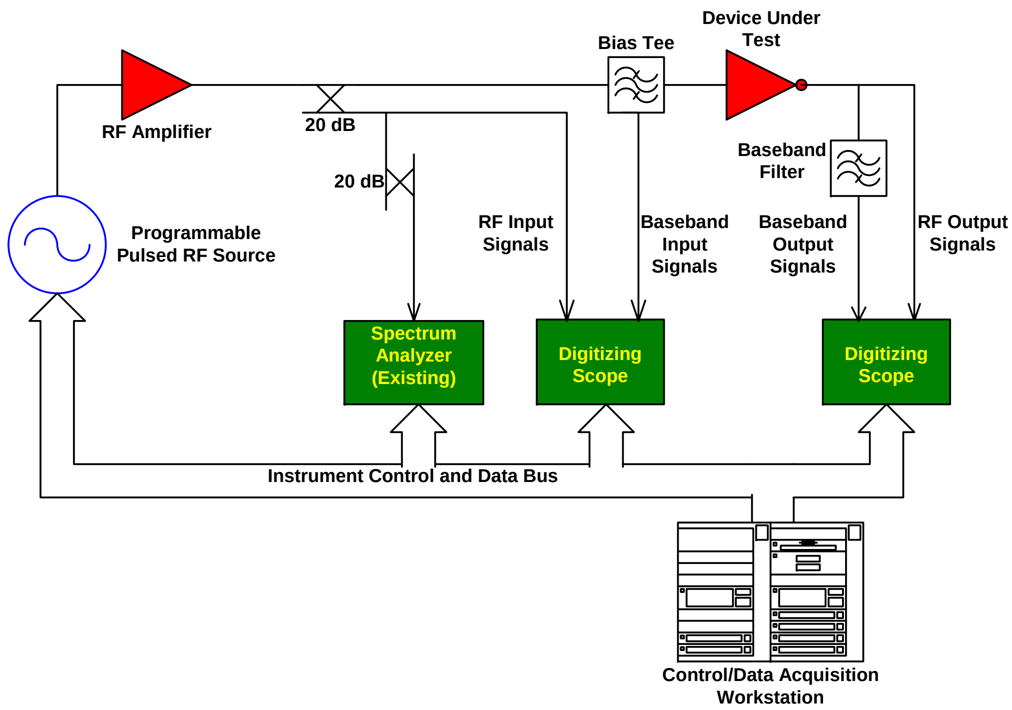
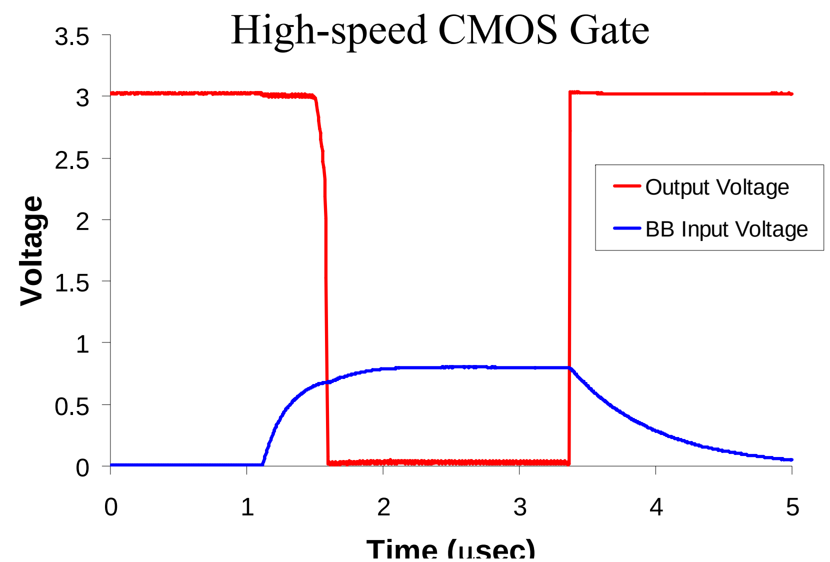
Outline

- Overview of results and contributions by UMD HPM Effects Research Group to the MURI Program
  - Results of experimental measurement and characterization of HPM effects at the device and circuit levels.
  - Investigation of effects from complex HPM waveforms
  - HPM effects in electronic networks and systems.
- Model of HPM effects in semiconductor circuits
  - Complement to RCM analysis of complex structures
  - Simple, scalable and based on physical device parameters
  - Compatible with existing high-frequency circuit simulators
  - Accurate predictor of susceptibility in existing and advanced circuits and systems

Effects Testing of Integrated Circuits

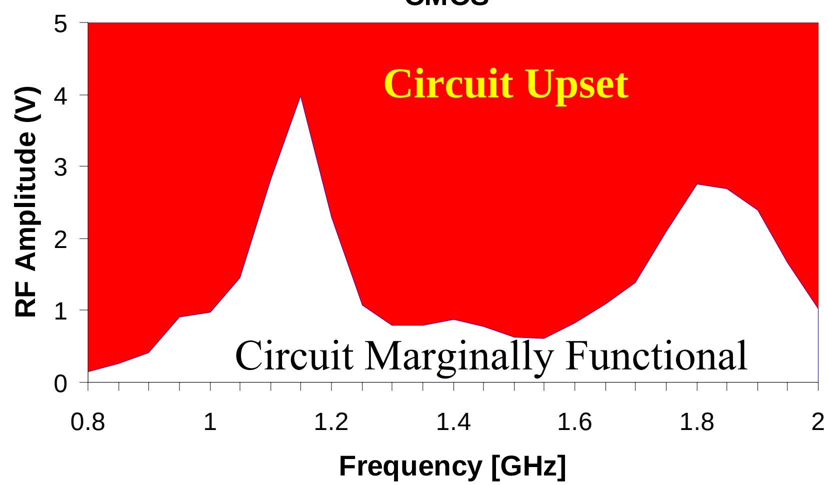




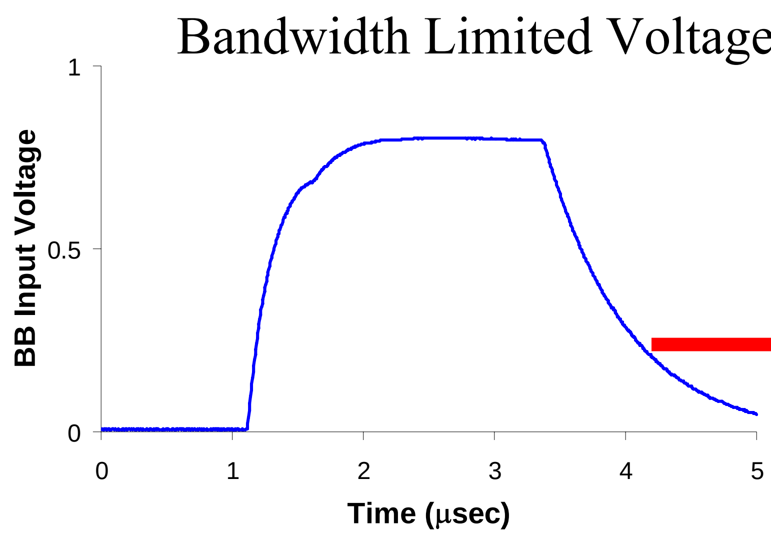
•Onset of effects $0.25 < V_{RF} < 1$ V

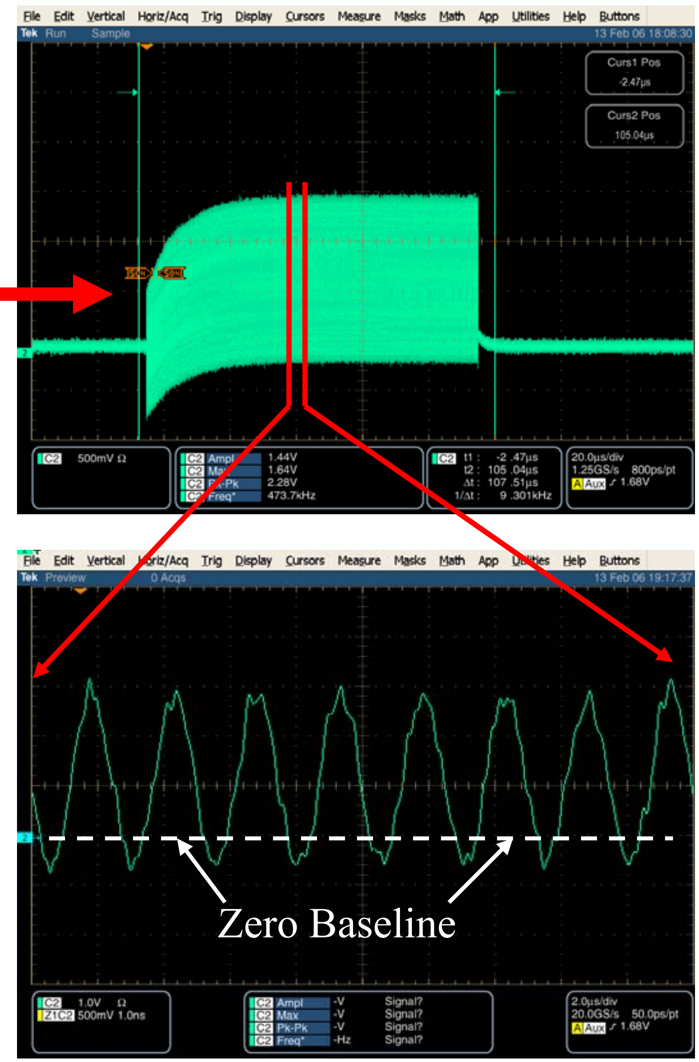
•Depend on RF frequency, pulse width, modulation, logic state, bias voltage, bus impedances, surrounding circuitry….

•Typically pulse widths > 100 nsec are required



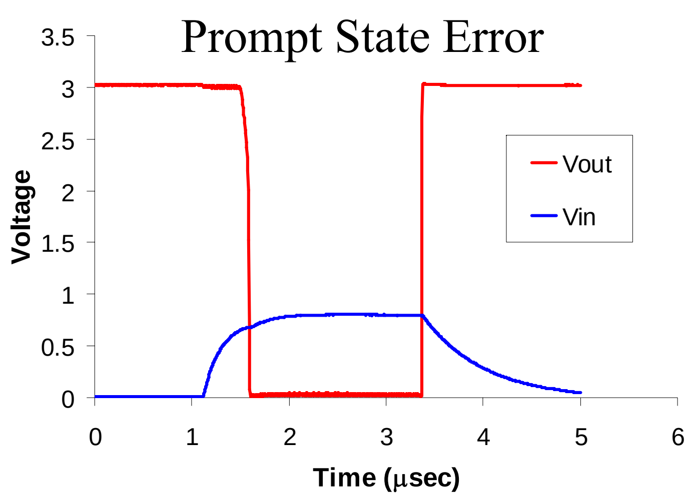
RF voltage at the input of a typical CMOS

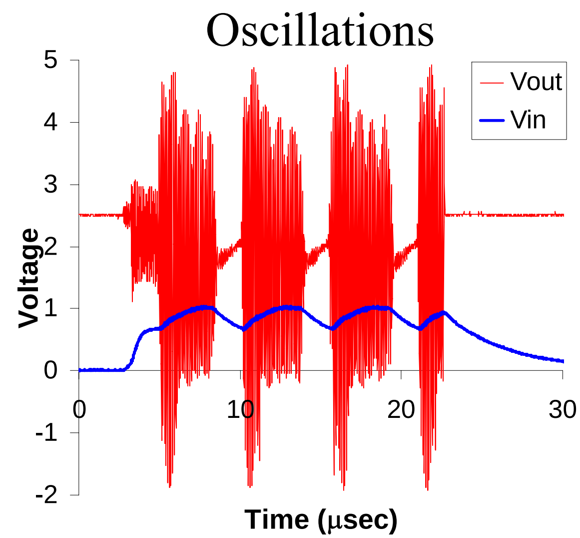


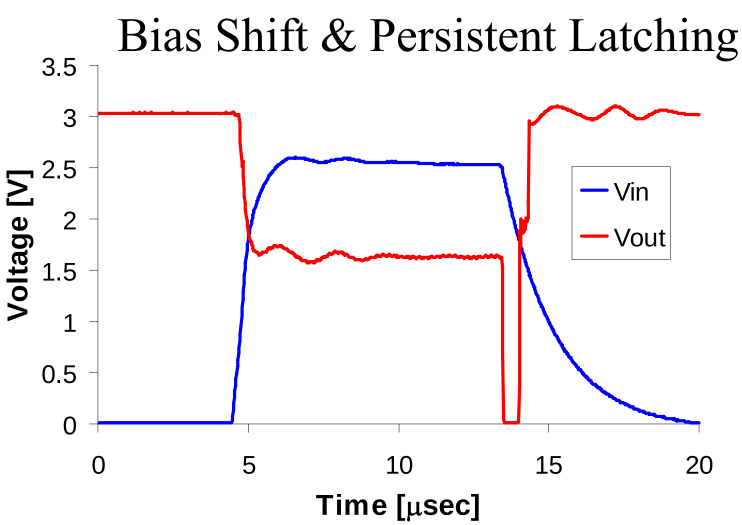


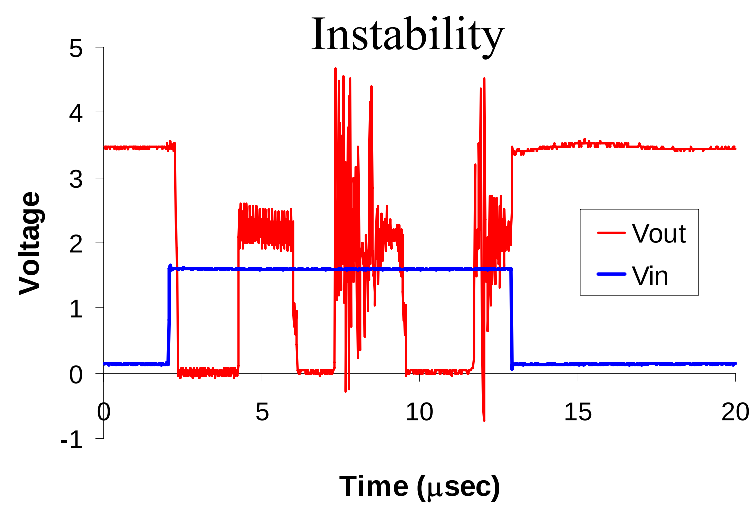
Expanded view showing actual RF cycles.

Examples of Effects in Advanced CMOS

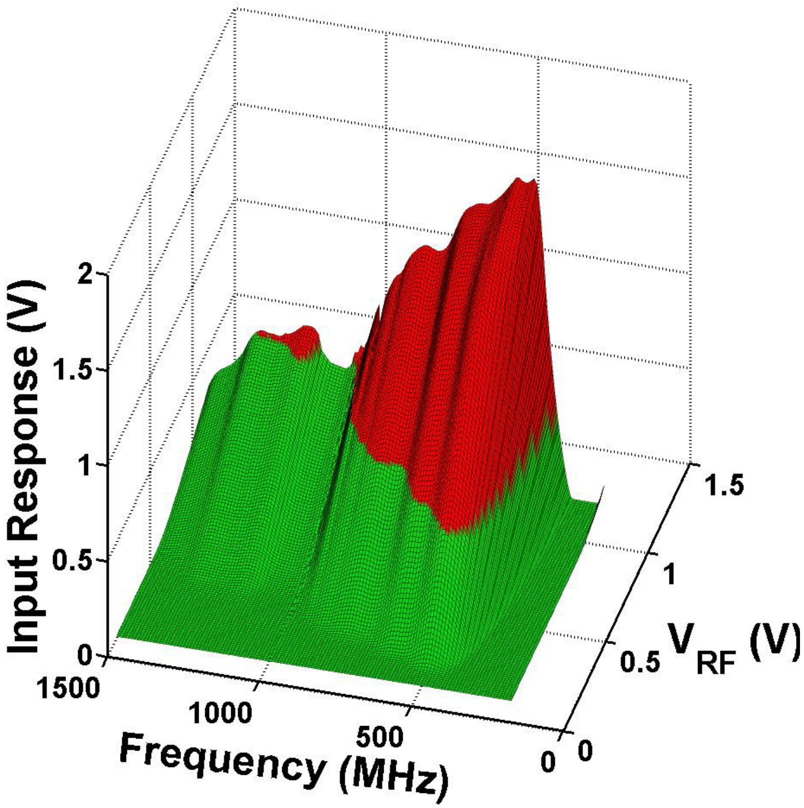




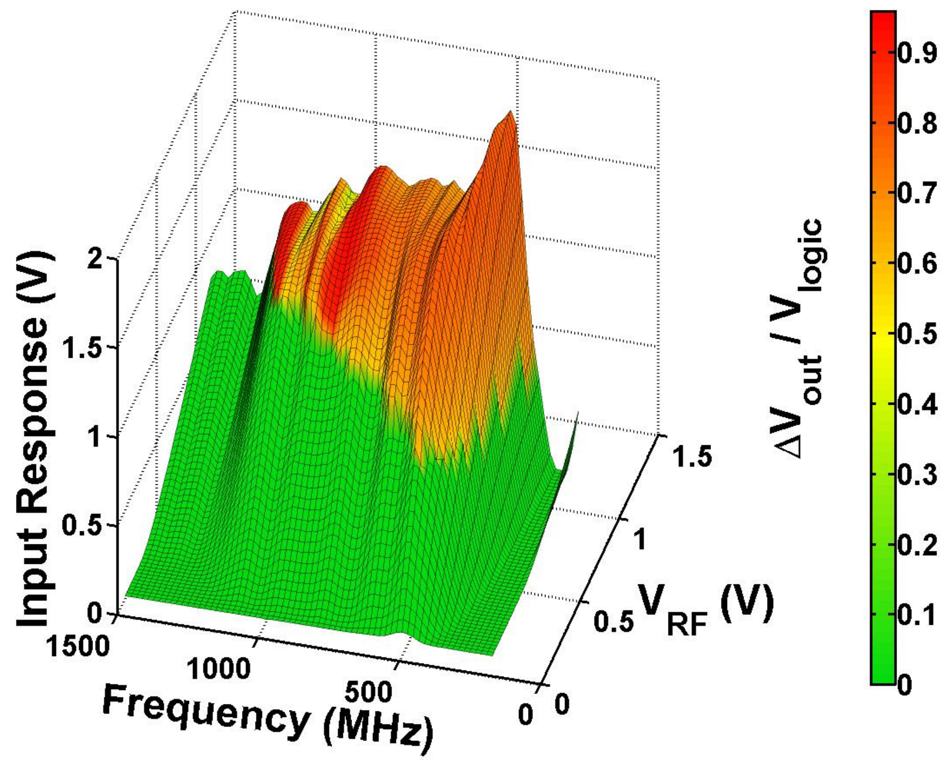




Mapping RF effects in integrated circuits

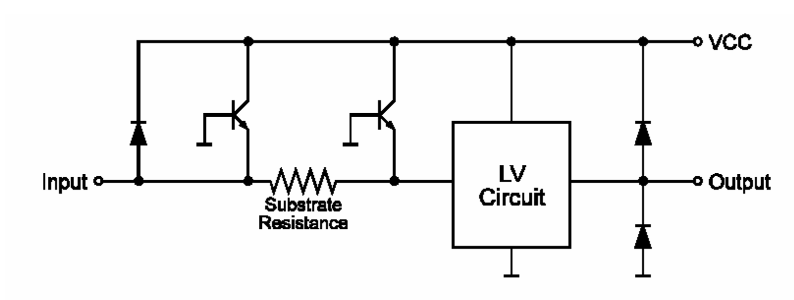


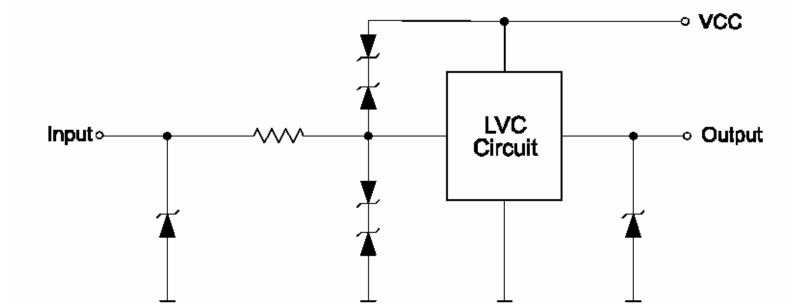
High-speed CMOS

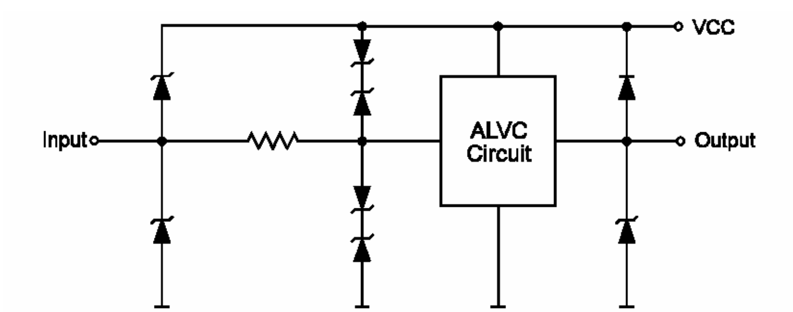


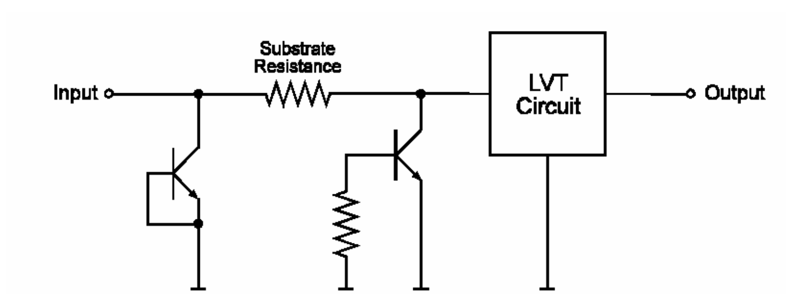
Advanced Low-voltage CMOS

Examples of ESD protection in integrated circuits



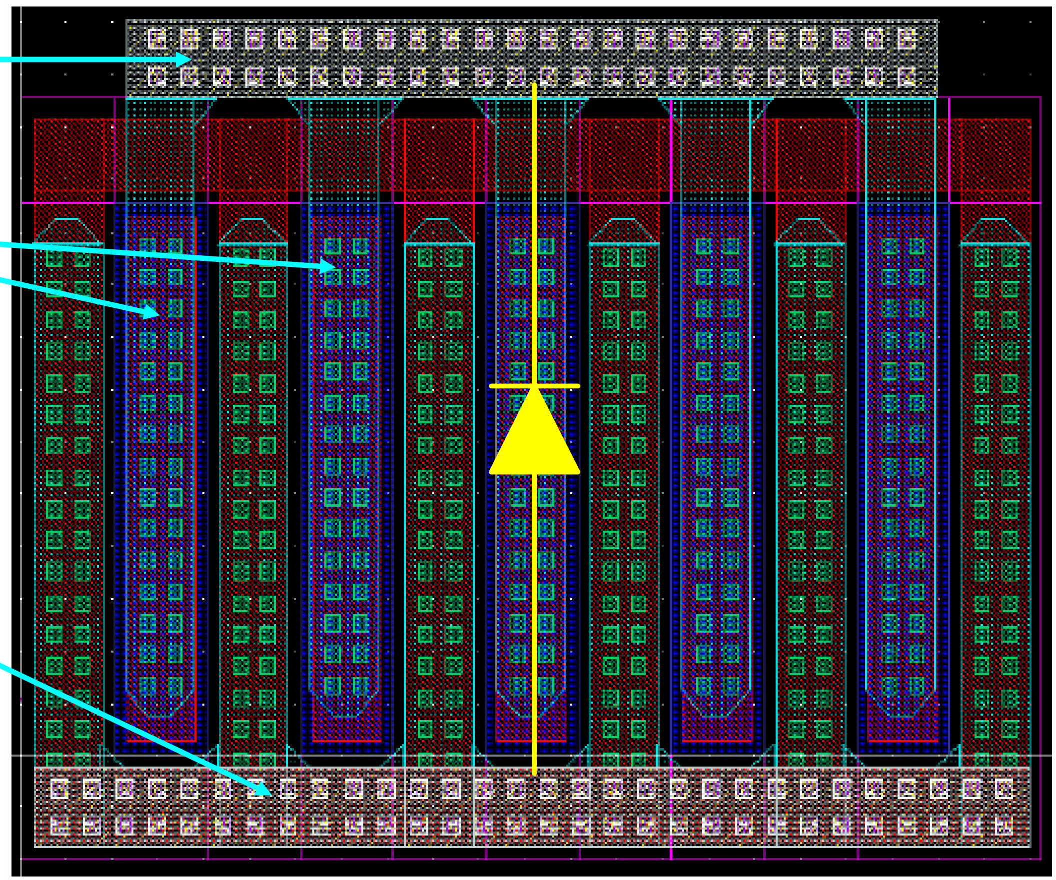






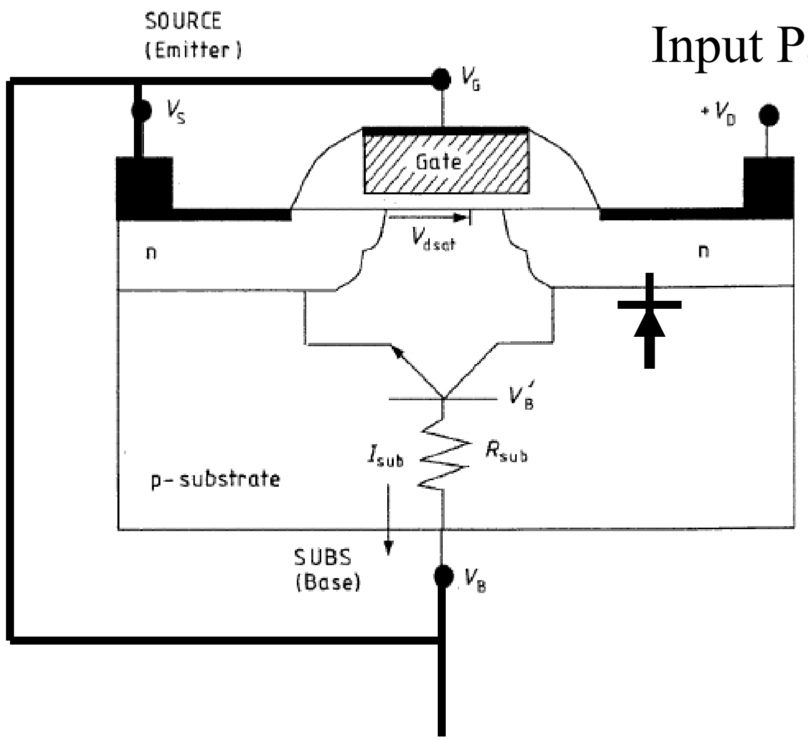
Electrostatic discharge protection devices are integrated into virtually all integrated circuits: discrete, logic, analog, RFIC, mixed signal

Physical Layout of ESD Protection Device

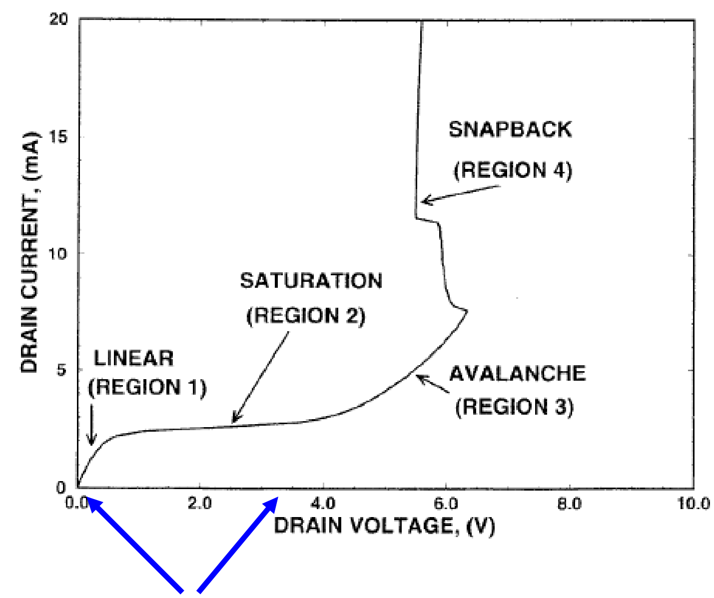


Electrical and Physical Characteristics of ESD Devices

Input Pad

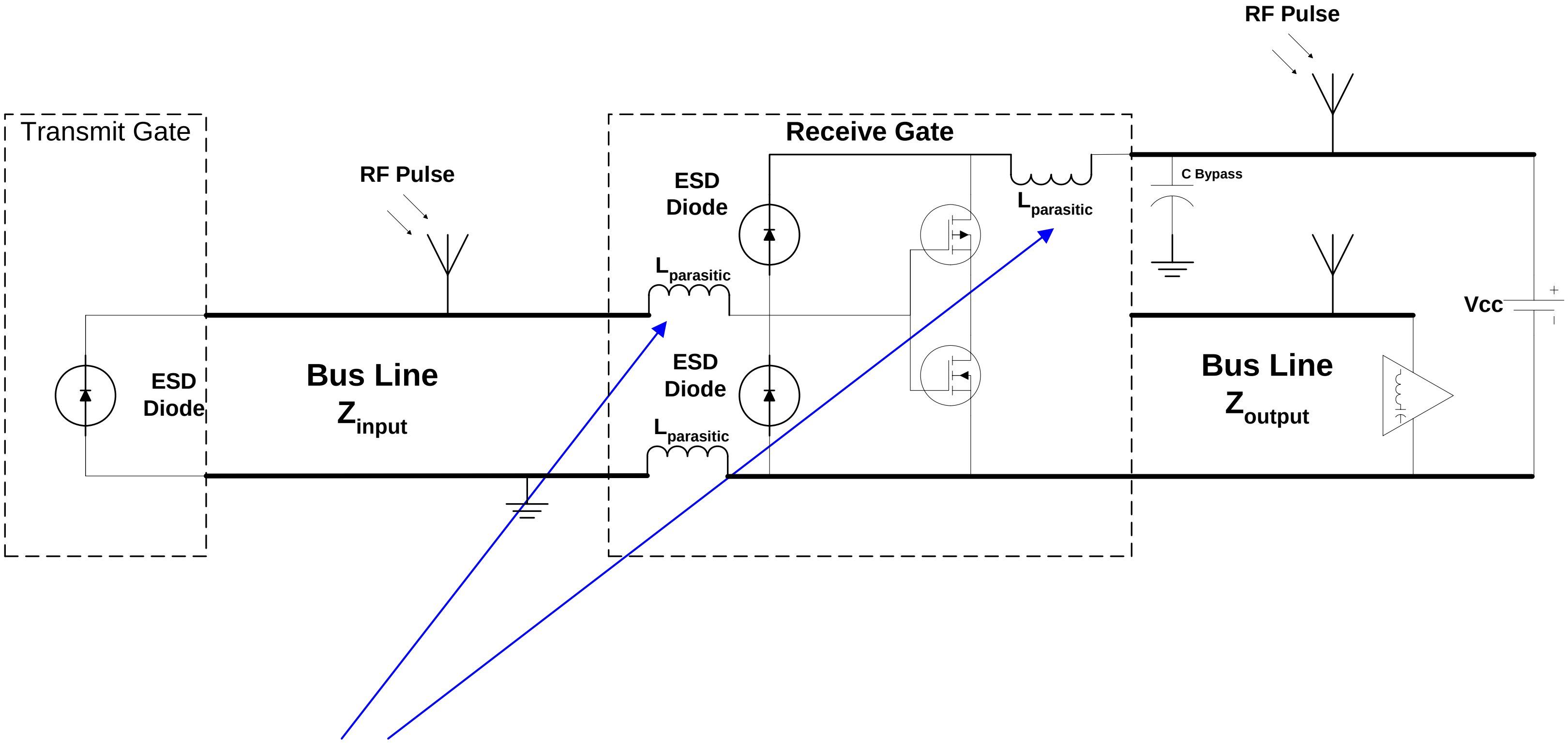


Ground (V_{ss})



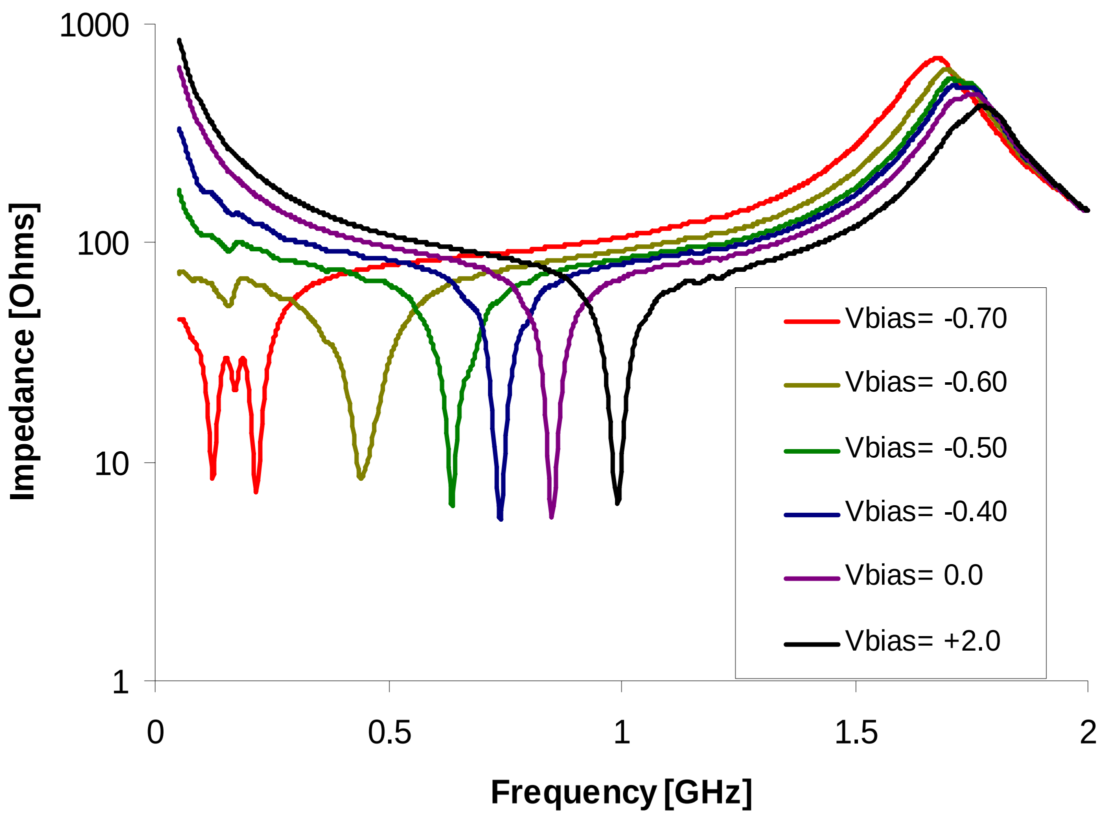
Typical range of voltages relevant for HPM effects

Simplified Schematic of a CMOS Circuit



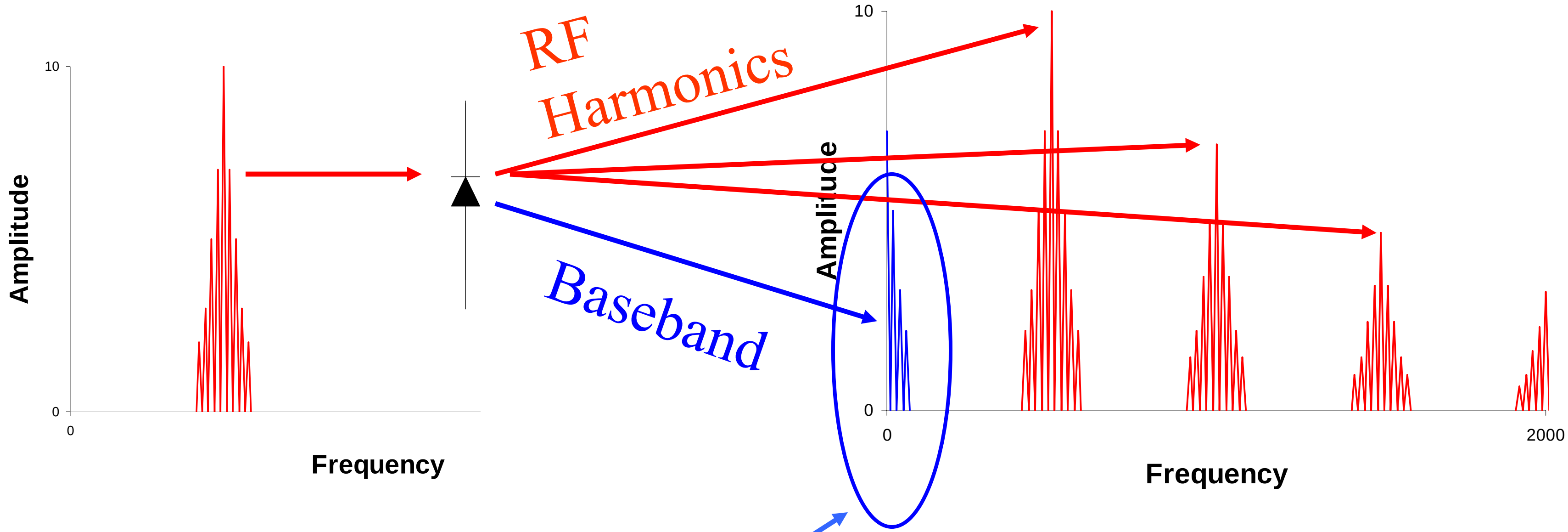
Resonant circuits consisting of lumped and distributed parasitic elements

Impedance at the input of high-speed CMOS logic circuit



- When driven at resonance, the diode current and the rectified voltage increase.

The ESD diodes down-convert the modulation frequencies off the microwave carrier



These frequencies trigger CMOS operation

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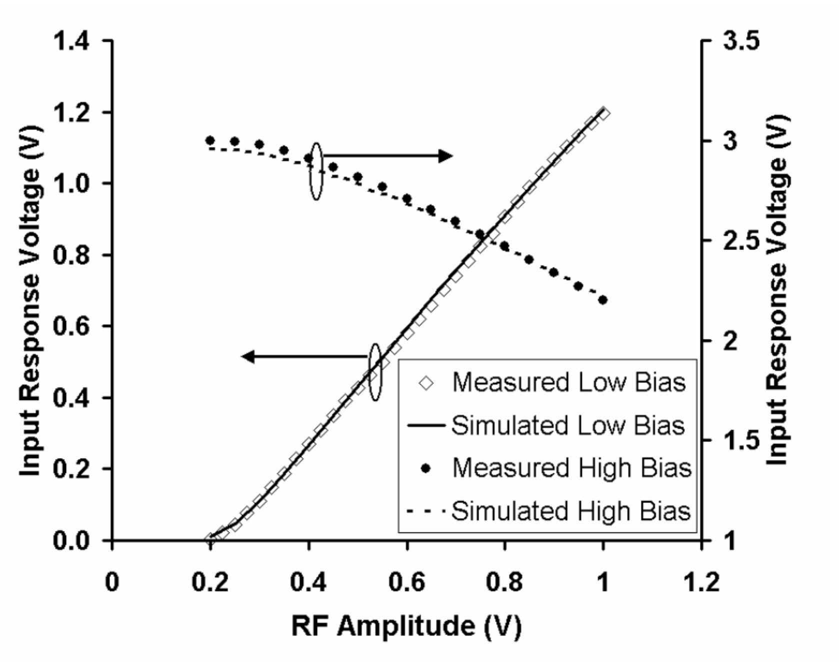
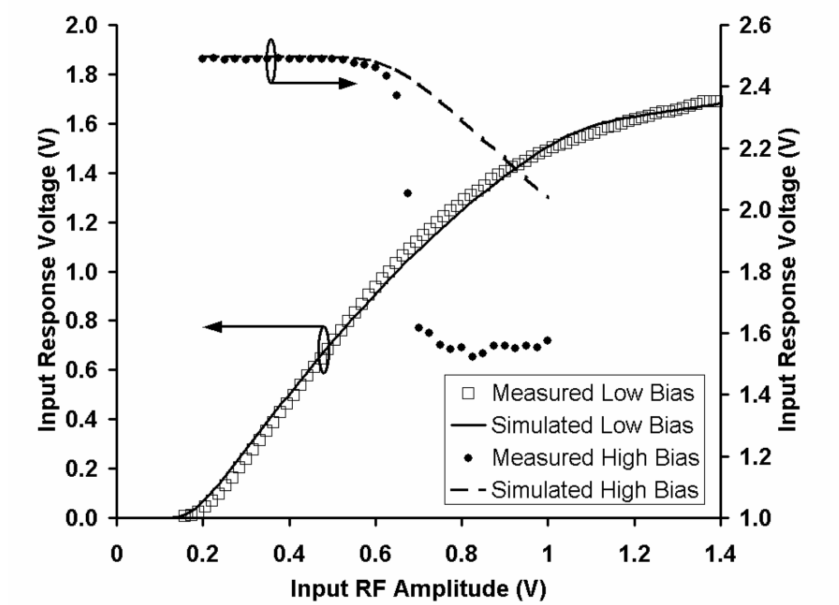
Comparison of measured and simulated response using model parameters extracted from small-signal measurements



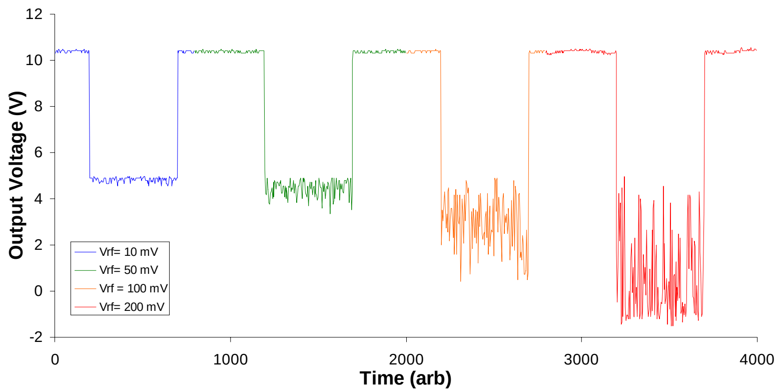
High-speed CMOS Logic

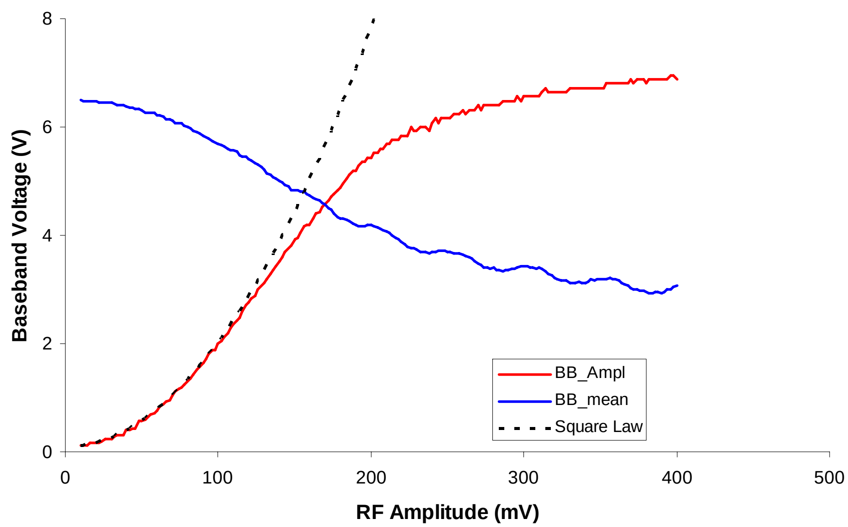


Advanced Low-voltage CMOS

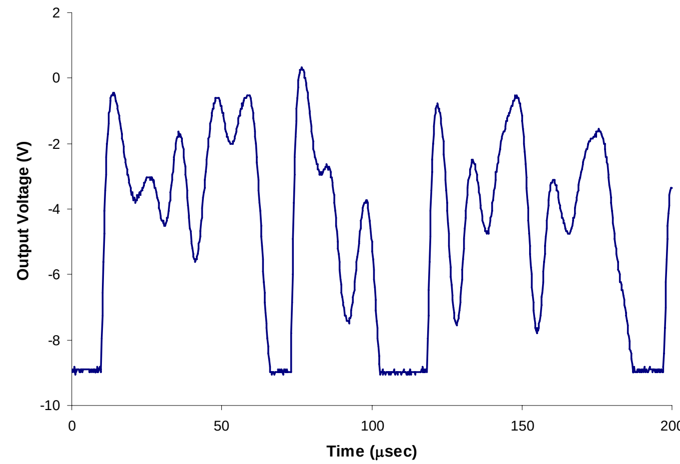
This behavior has been observed and studied in a wide variety of circuits.

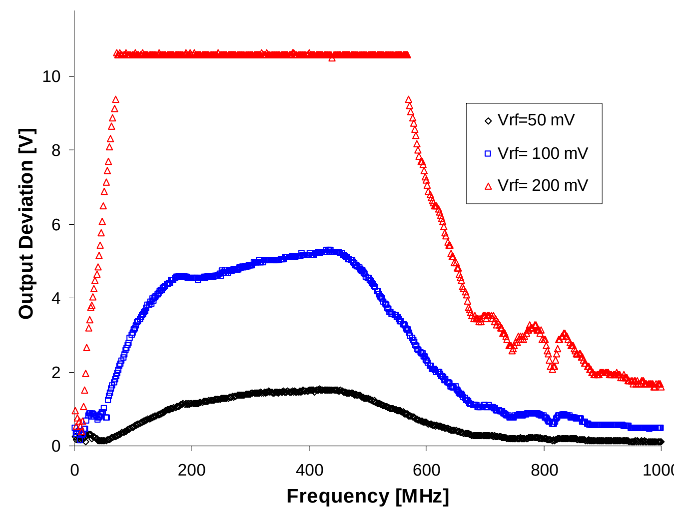
Discrete (JFET)



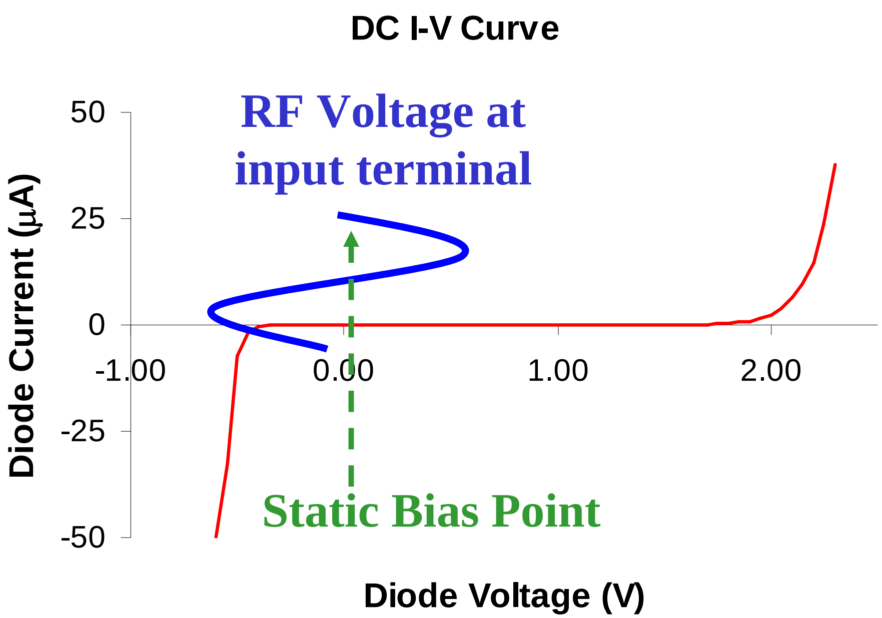


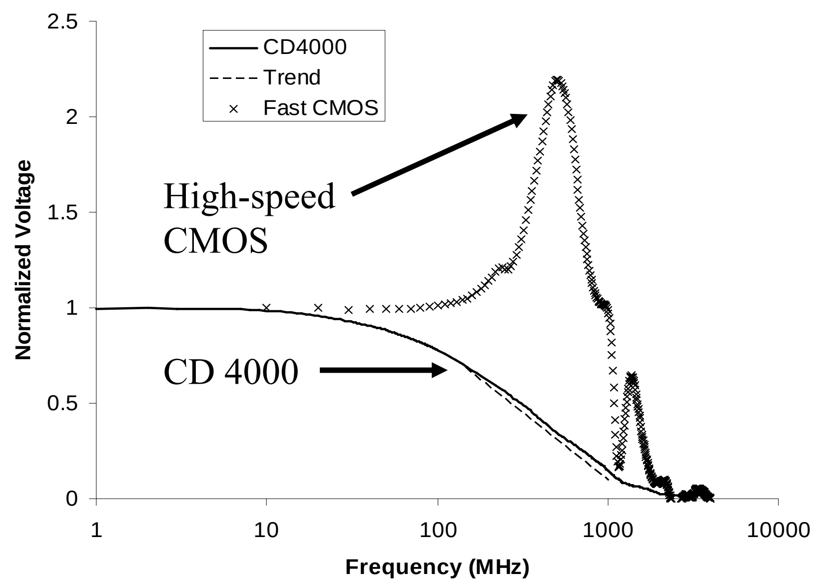
Analog (Op Amp)





Are these parasitic diodes good rectifiers at microwave frequencies (f > 300 MHz)?



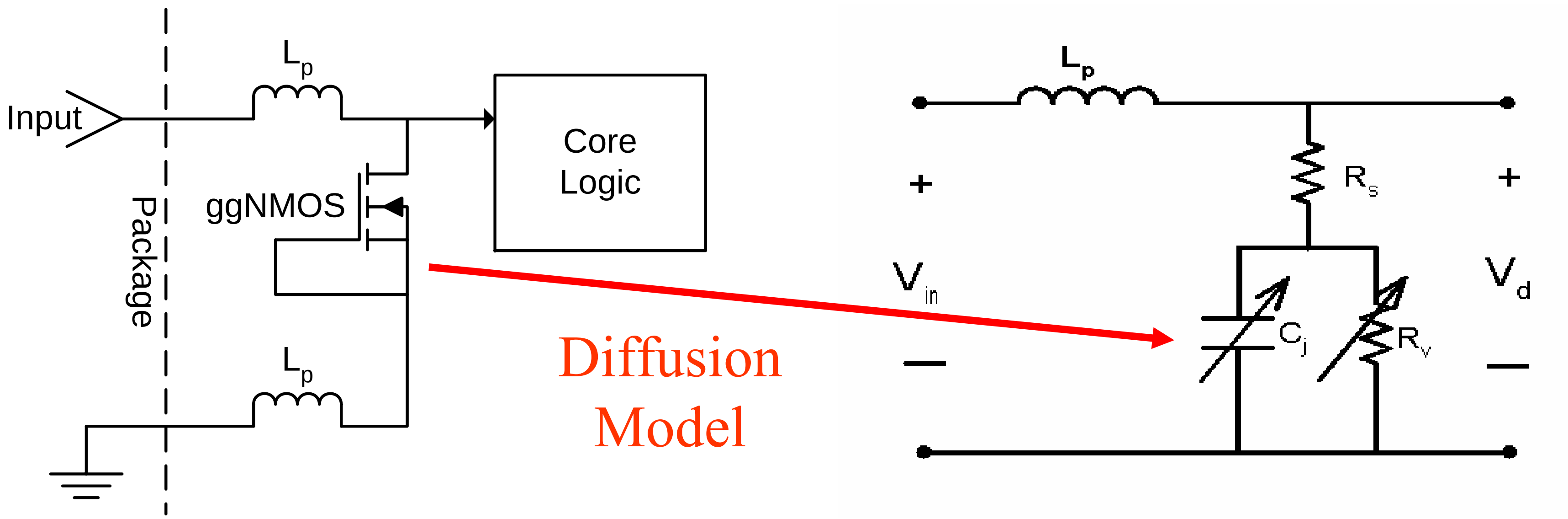


• W. Crevier, "Rectification Equivalence: A method for characterizing semiconductor rectification," *Titan-Jaycor internal report to DTRA*, December, 1996.

•M. L Forcier, R. E. Richardson, " Microwave rectification RFI response in field-effect transistors," *IEEE Trans. Electromag. Comp., vol. EMC-21, no. 4, Nov. 1979.*

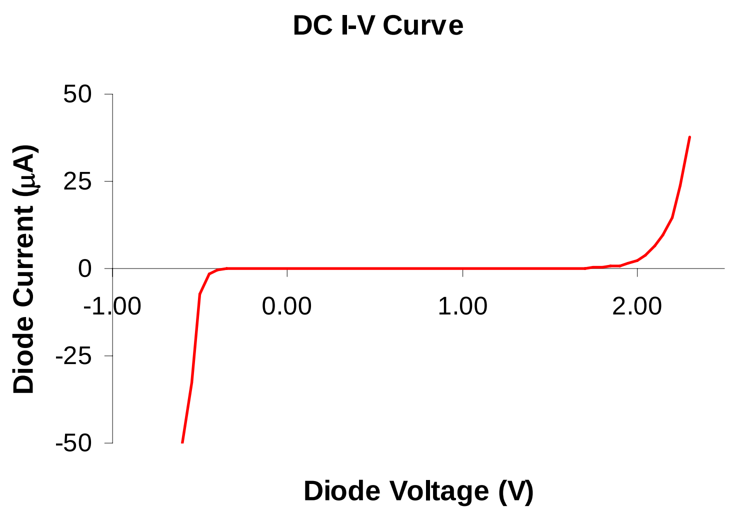
•D. J. Kenneally, G. O. Head, S. C. Anderson, "EMI noise susceptibility of ESD protect buffers in selected MOS devices," *Proc. IEEE Int. Conf. Electromag. Comp.*, Wakefield, MA, August, 1985, pp. 251-261.

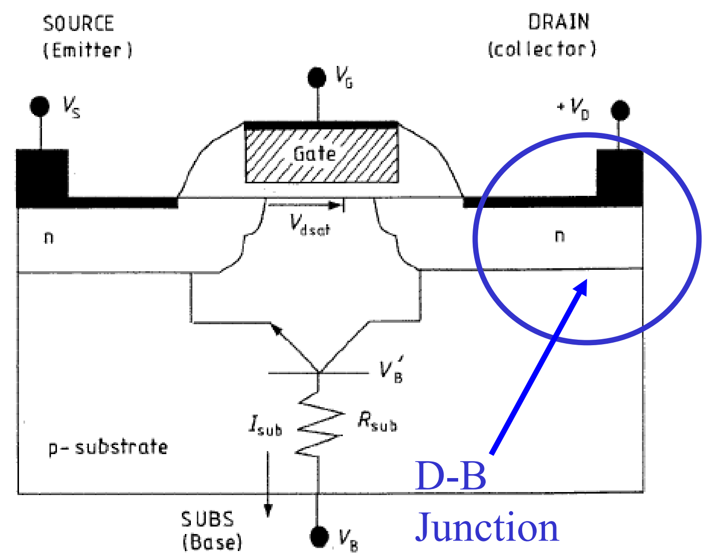
The “rectification” model does not a complete the picture



Model of Drain-Bulk Diode in CMOS

High-Frequency Analysis of D-B Junctions





$$\frac{\partial \Delta p(x,t)}{\partial t} = D_p \frac{\partial^2 \Delta p(x,t)}{\partial x^2} - \frac{\Delta p(x,t)}{\tau}$$

← Time-dependent Diffusion Equation

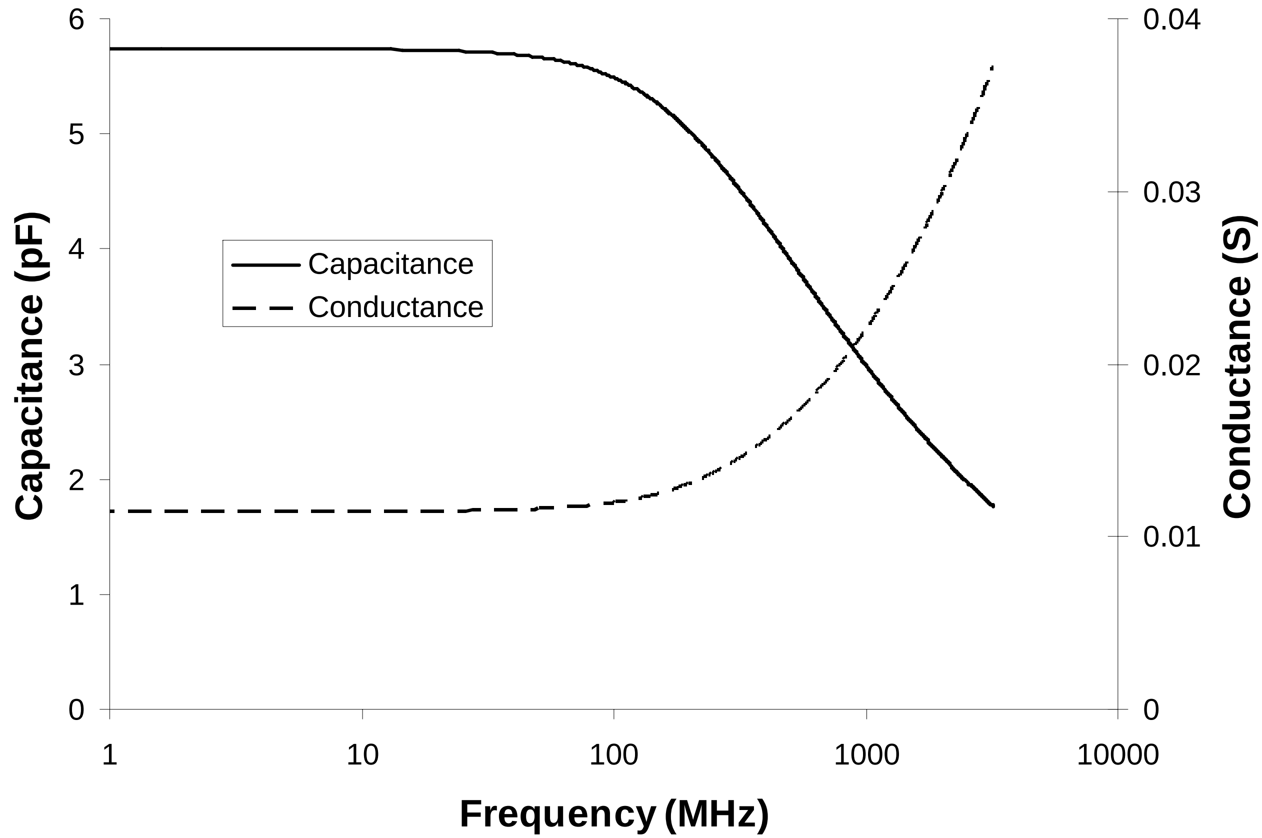
$$I_{diff} = qA \frac{D_p}{L_p} \frac{n^2}{N_D} (e^{\frac{qV_d}{kT}} - 1)$$

← Solution for "Abrupt" Boundary Conditions

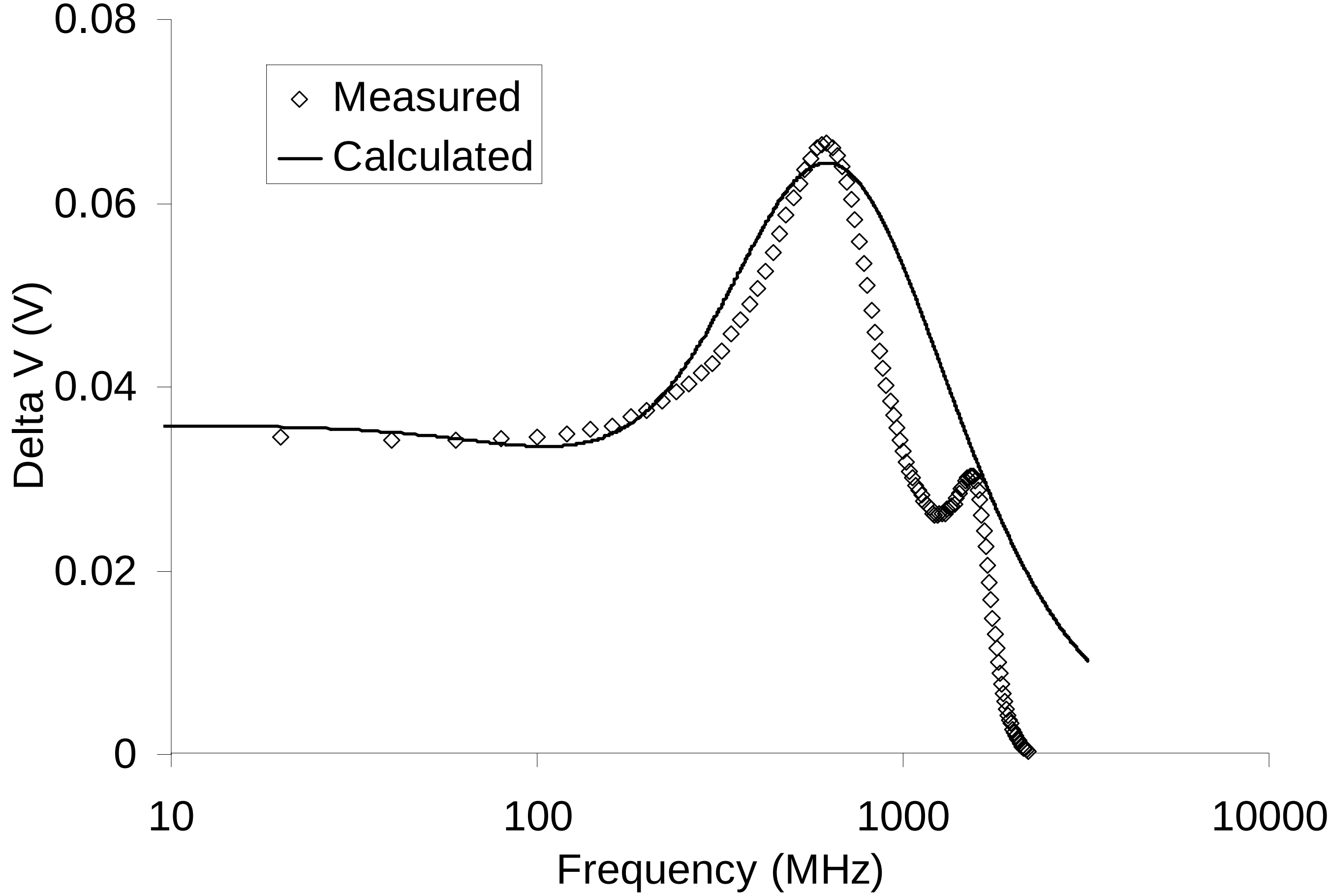
$$Y_D = \frac{i_D}{v_D} = G\sqrt{1 + j\omega\tau}$$

← High-frequency Admittance

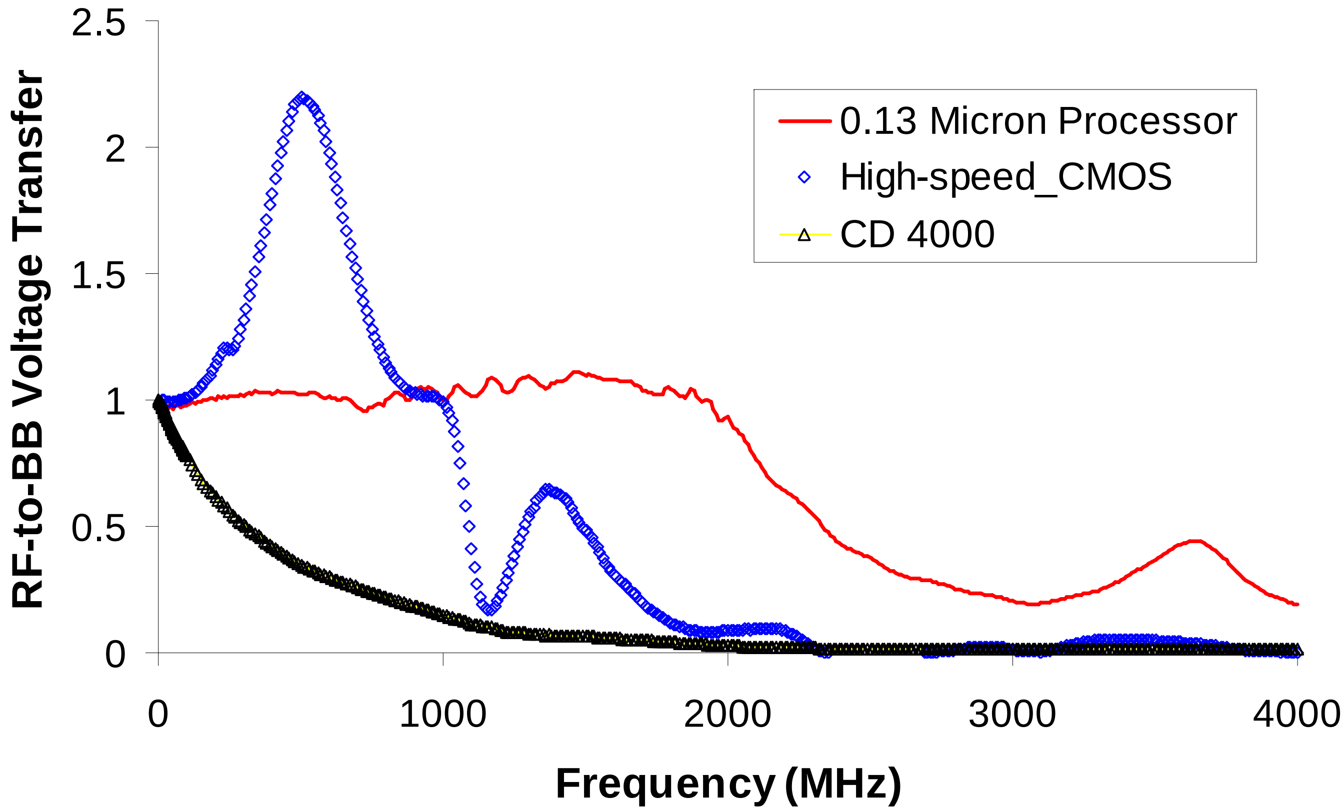
High-Frequency Admittance of D-B Junctions ($I_s = 10^{-15}$ A, $V_{th} = 0.025$ V, $\tau = 5$ nsec)



Comparison of measured and calculated D-B sensitivity in advanced low-voltage CMOS (τ = 5 nsec)



Comparison of the D-B junction sensitivity in micron-scale logic

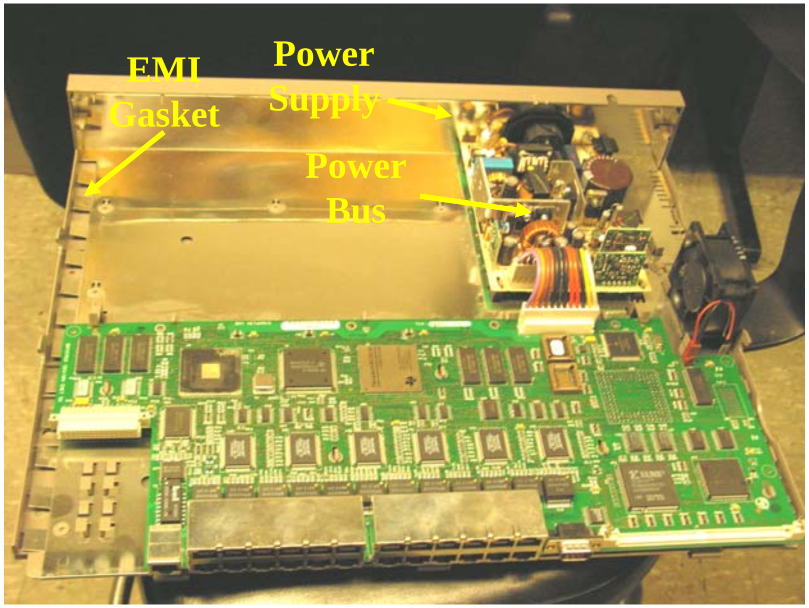


Overview of studies of HPM upset in electronic systems

•Systems consist of many circuits with internal resonances interconnected by transmission lines within complex cavities.

•What parts of the system are most likely to be upset once RF penetrates the enclosure?

View of the assembled LAN switch



Chassis cover removed

Distribution of parasitic resonant frequencies and quality factors in a digital communications system

View of the IC layout on the motherboard of a programmable LAN switch

I/O

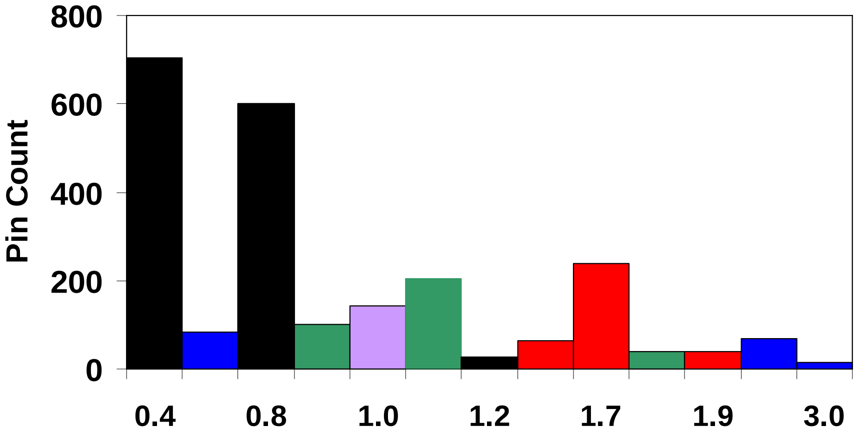
Logic

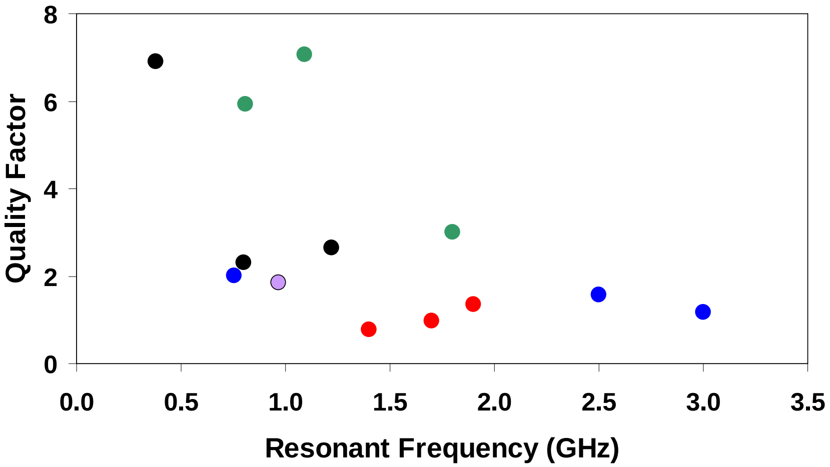
System Controller

CPU

Memory

Results from small-signal measurements of parasitic resonances in the IC's of a functional set



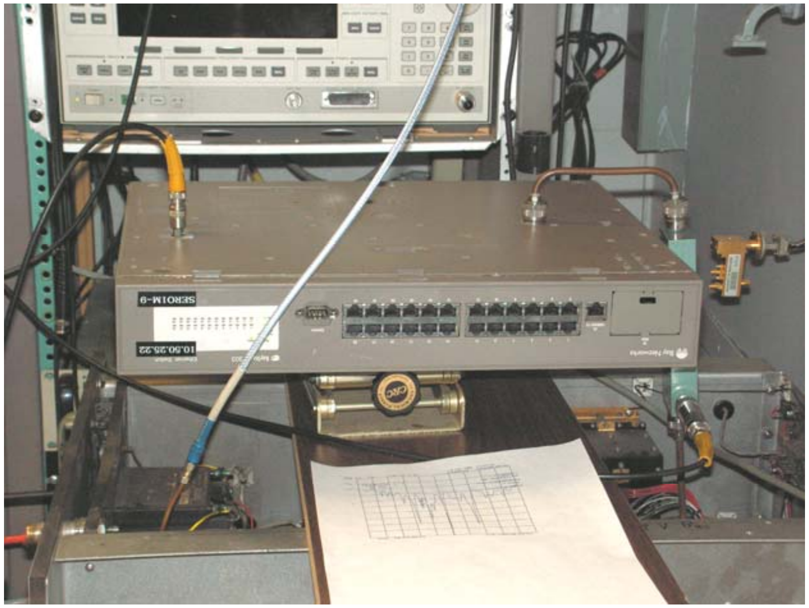


Characteristics of electronic systems

• Most electronic systems contain modular components that are packaged according to standardized form factors (4U, 19” bays, ATX, etc.)

•Does this present any universal conditions or likely avenues for HPM attack?

•The enclosures are clearly natural microwave resonators.

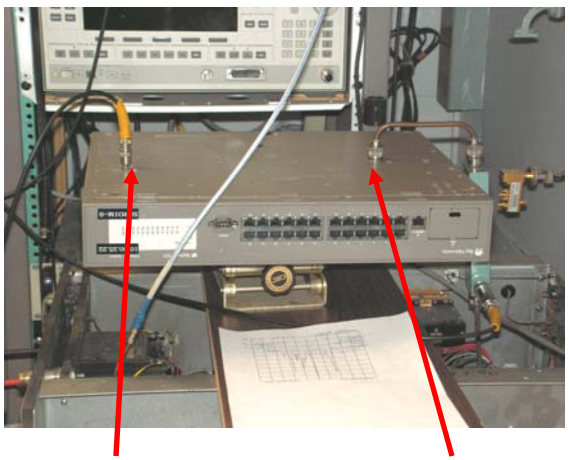


LAN switch with coaxial RF ports

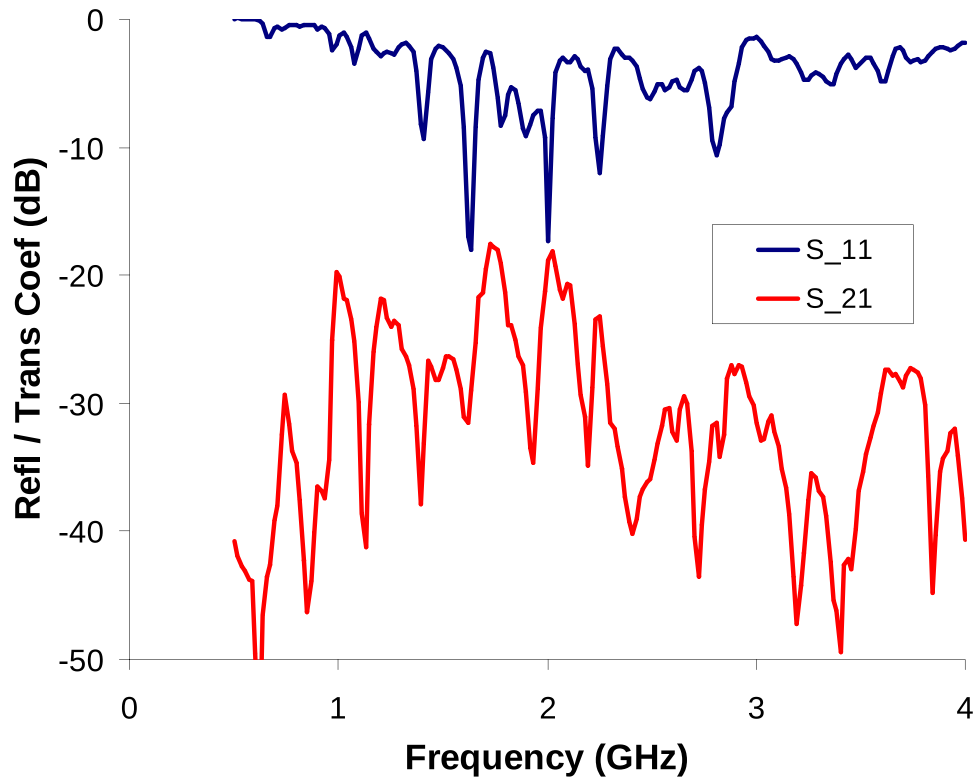
PC with waveguide port

Results of S-parameter measurements in an operating LAN switch

• Port #1 is a dipole launching antenna and port #2 is connected to the main +12 VDC power bus on the motherboard

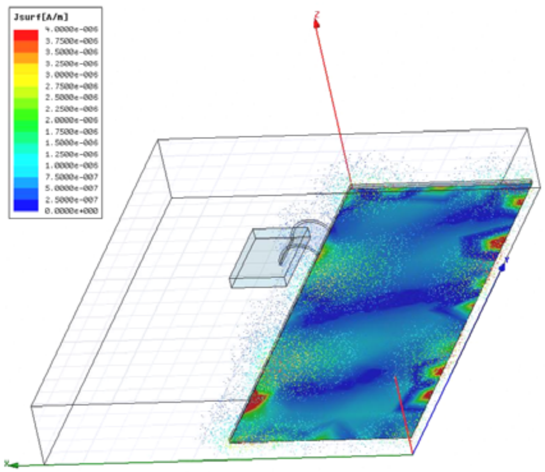


Port #2 Port #1

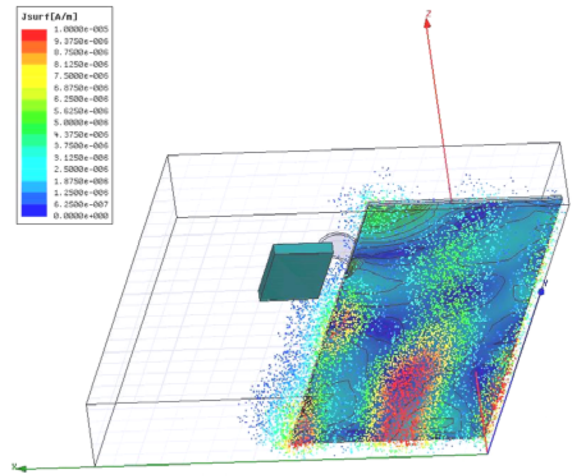


• Strong resonances are observed across L-band (~1-2 GHz)

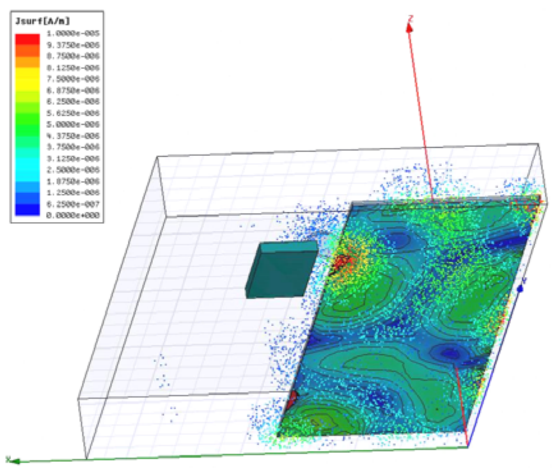
RF Surface Current Density for Various TEM Eigenmodes on the Motherboard



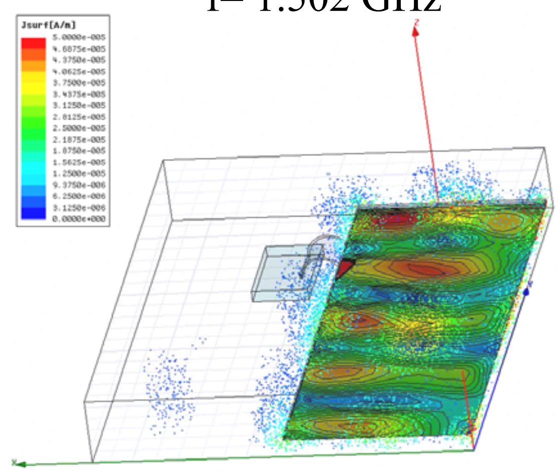
f= 1.284 GHz



f= 1.502 GHz

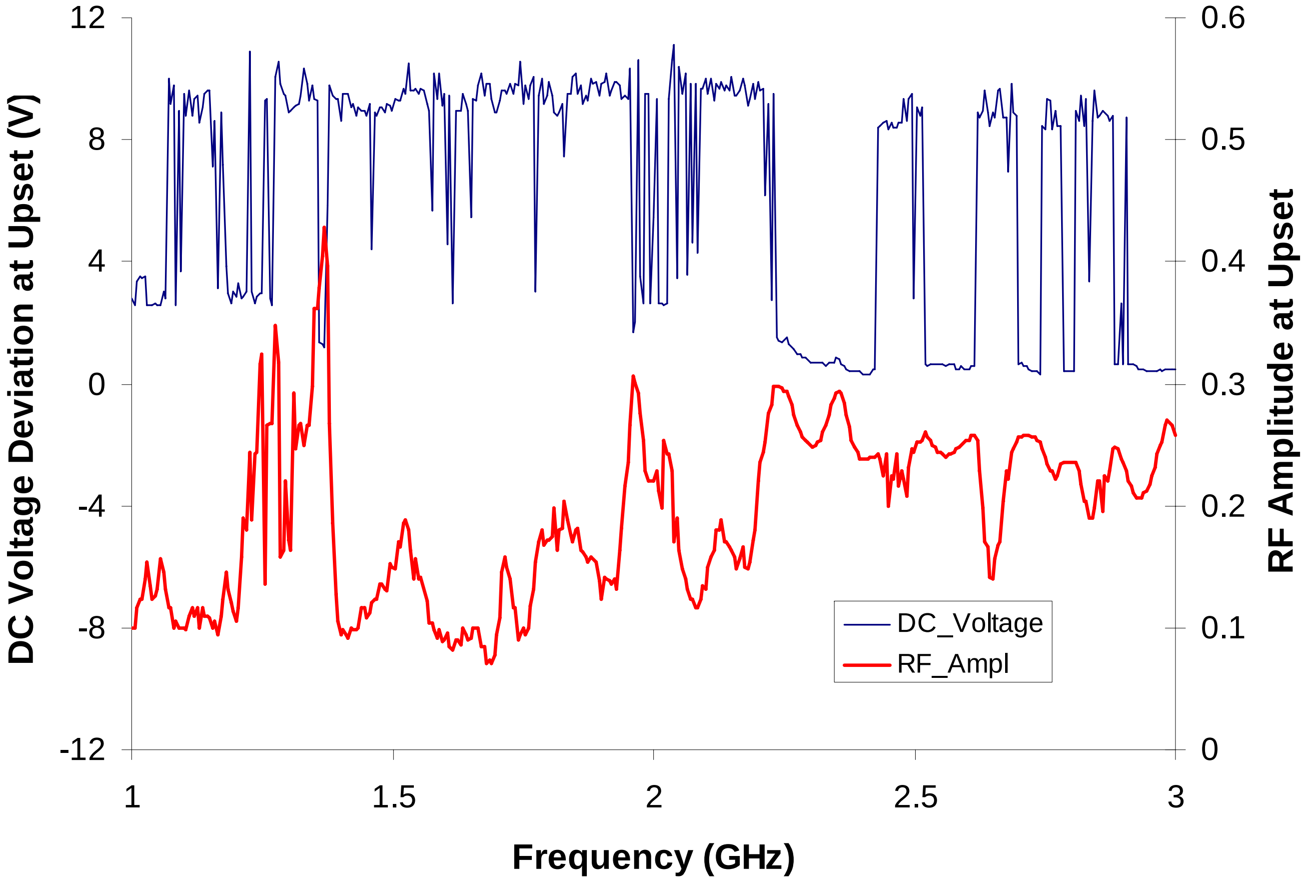


f= 1.591 GHz



f= 1.654 GHz

Results from Upset Studies in a LAN Switch



•At upset, the RF caused the switching power supply to either completely shut down or output the incorrect voltage for times that were 100 – 1000 times the RF pulse width.

•This forced the microcontroller to completely reboot the system.

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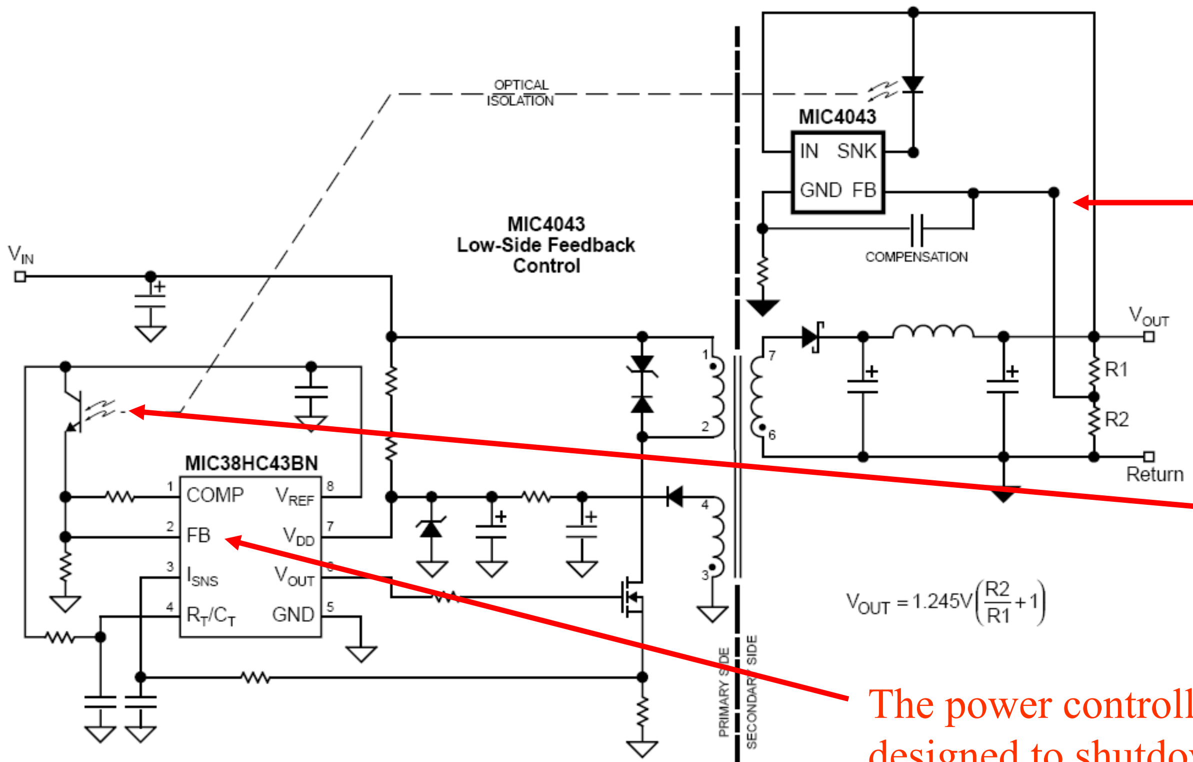
Schematic of a typical switching power supply



200kHz DC-DC Flyback Converter

Rectified RF voltage at the feedback pin fools the comparator into detecting an over-voltage condition. It then sends a shutdown signal to the power controller via an opto-isolator

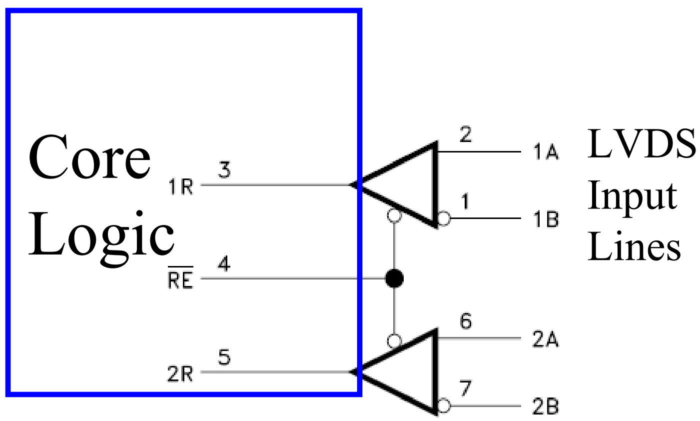
The power controller feedback is designed to shutdown the system (~ 30 sec) even if the "fault" is momentary (microseconds).

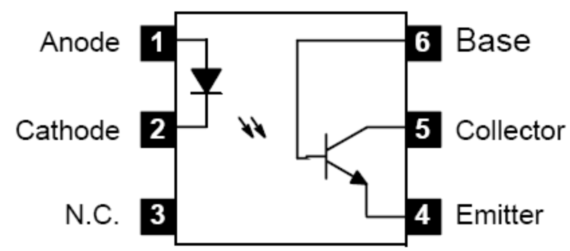
Conclusions

- RF rectification by ESD protection diodes and parasitic resonances have been identified as major susceptibility issues.
- The RF characteristics of these devices can be accurately described using lumped-element circuit models with simple high-frequency diode parameters.
- Upset can be easily predicted in terms of the high-frequency transfer characteristics of the circuit and the RF voltage, frequency and modulation at the circuit terminals.
- In systems, the problem requires an EM or RCM treatment.
- Power controllers with feedback have been identified as a major and universal problem.
- An informed basis for developing effects sources:
  - L-band
  - Wideband or chaotic modulation
  - 10-100 MW Power levels

Possible Solutions

- Low-voltage differential signaling between critical communications nodes
- New concepts for opto-isolation, low-power diodes, single photon detectors, etc.
- Power supply redesign
- New ESD circuits and structures





Students and Academics

- Student Research Assistants: Kathryn Chang, R. Mac Laren,
- Sponsored research: Calvin Cheung
- REU Interns: L. Goodman, M. Adan, K. Konstantine, S. Vora,
- UMD ENEE 499 Advanced Lab, “HPM Effects in Communications Electronics: B. Yeshitla, H. Lee, M. Stamm, M. Brill
- UMD Gemstone Honors Program

Publications, Invited Talks, Mini-courses 2004-present

1. T.M. Firestone, J. Rodgers and V.L. Granatstein, “Response of CMOS Logic with Electrostatic Discharge Protection to Pulsed Microwave Excitation Submitted to IEEE Trans. on Circuits and Systems.
2. T. M. Firestone, “RF Induced Nonlinear Effects in High-Speed Electronics" Masters of Science Thesis, University of Maryland, May 2004.
3. J. Rodgers, T. Firestone, V. L. Granatstein, V. Dronov, T. M. Antonsen, Jr., and E. Ott, “Study and applications of wideband oscillations in high-power pulsed traveling-wave tubes,” *Proceedings of the Sixth International Vacuum Electronics Conference IVEC 2005*, Noordwijk, The Netherlands, April 2005.
4. J. Rodgers, “HPM upset in communications systems," Invited talk presented at the Defense Threat Reduction Agency workshop on Microwave Effects, Sept., 2005, Alb. NM.
5. J. Rodgers, “Nonlinear and chaotic effects in communications electronics from high-power microwave pulses,” Invited one-day minicourse presented to Defense Intelligence Agency 09 August, 2005, Hunstville, AL.
6. J. Rodgers, “Stochastic microwave sources for effects applications," invited talk presented at the Defense Threat Reduction Agency workshop on Microwave Effects, Sept., 2005, Alb. NM.