Simulation of Multi-Technology Micro and Nano Systems

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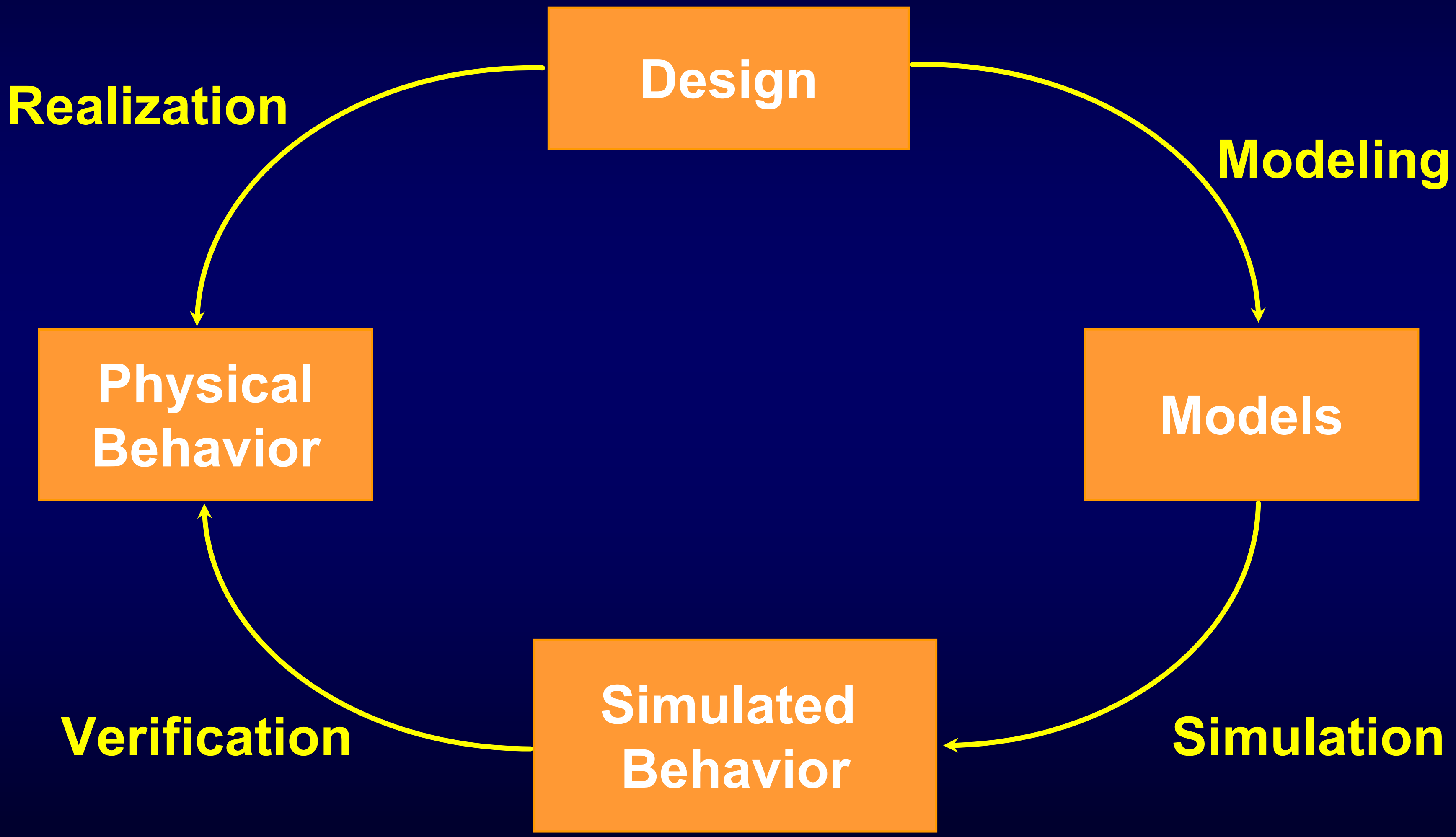
Outline

- **Introduction**
- **Coupled circuit/device simulation**
- **Advantages and applications to integrated circuits**
- **Examples of simulating microsystems**
  - Microfluidic flow
  - Electroosmotic flow
  - Piezoelectric micropower generator
  - Phase noise of MEMS RF VCOs

Role of Modeling in Design

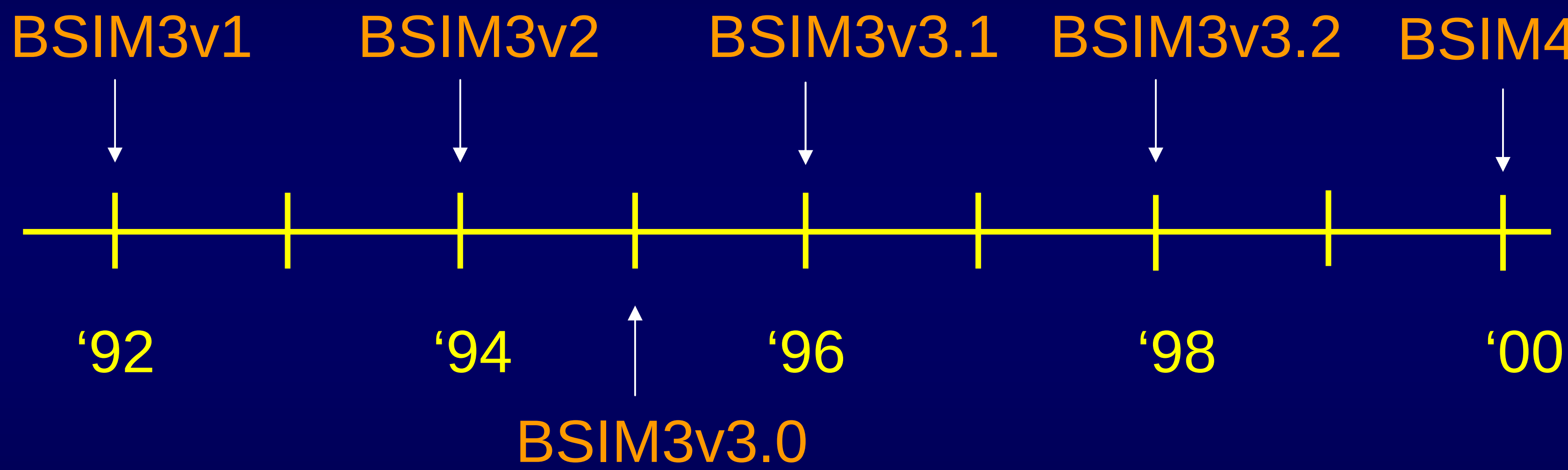


The Modeling Hierarchy

Speed ⟷ **Accuracy**

High-level models	Lumped-element models	Compact models	Numerical models
VHDL-AMS	**RLC**	**BSIM3**	**PISCES**
Verilog-A		**EKV**	**Medici**

A Case Study - BSIM3 MOSFET Model



- **Compact model development, implementation and validation takes several years**

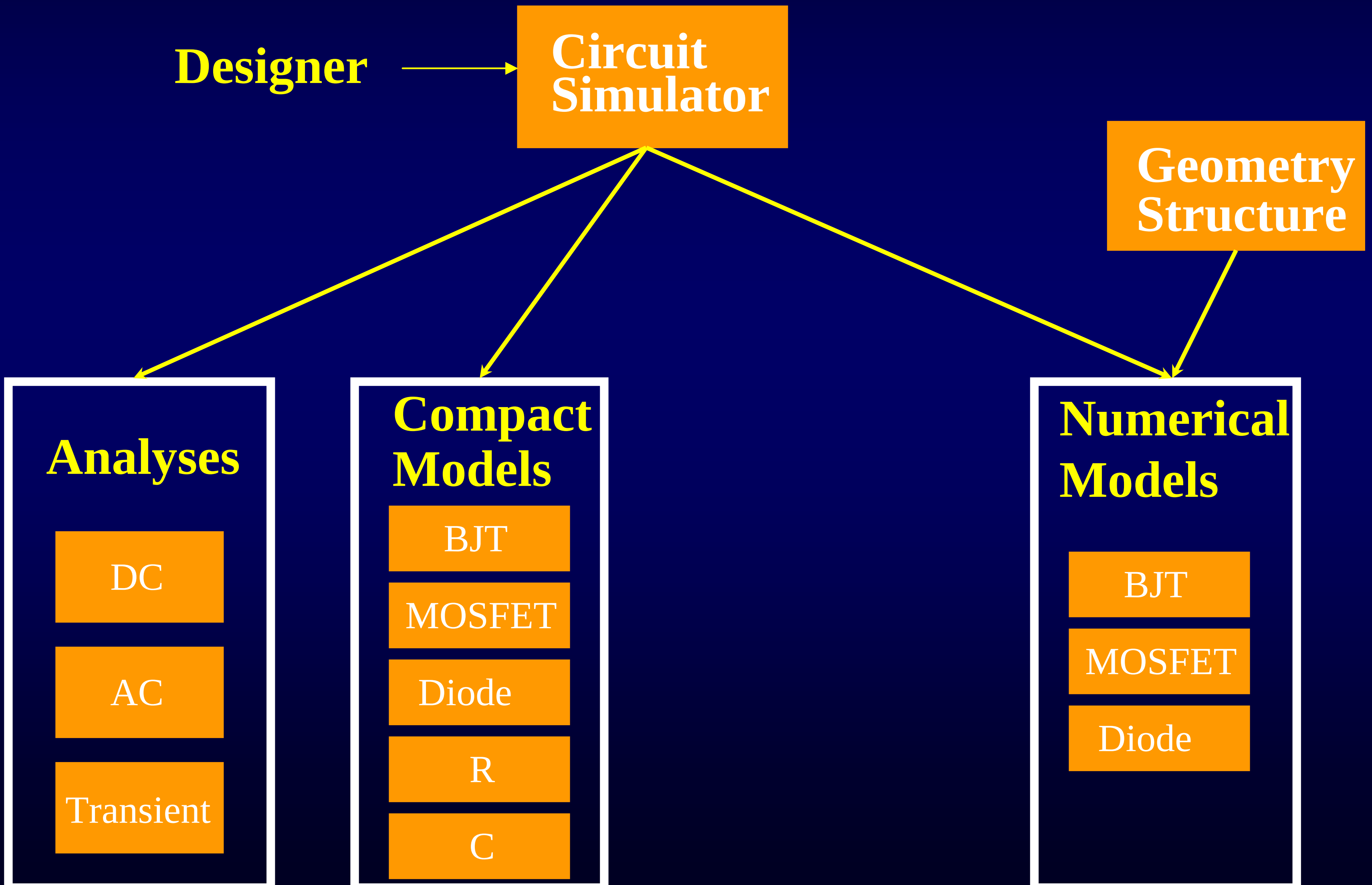
Circuit/Device Simulation

- **Circuit simulation**
  – Compact models used: inaccurate under certain conditions
  + Simulation of multiple devices in a circuit
- **Device simulation**
  + Based on device physics: accurate
  – Simulation of a single device, no circuit embedding
- **Coupled circuit/device simulation**
  + Accurate
  + Simulation of complete systems

Coupled Circuit/Device Simulator

- **Compact models for electronic components (BJTs, MOSFETs, …)**
- **Accurate numerical models for various components**
- **Analysis capabilities supported by the circuit simulator**

Coupled Circuit/Device Simulator

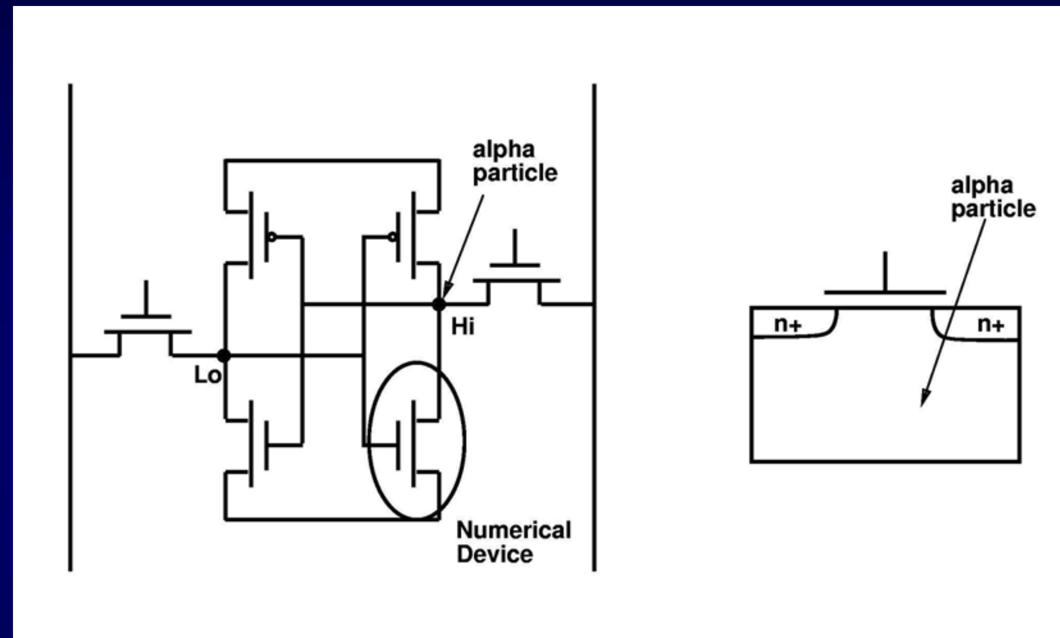


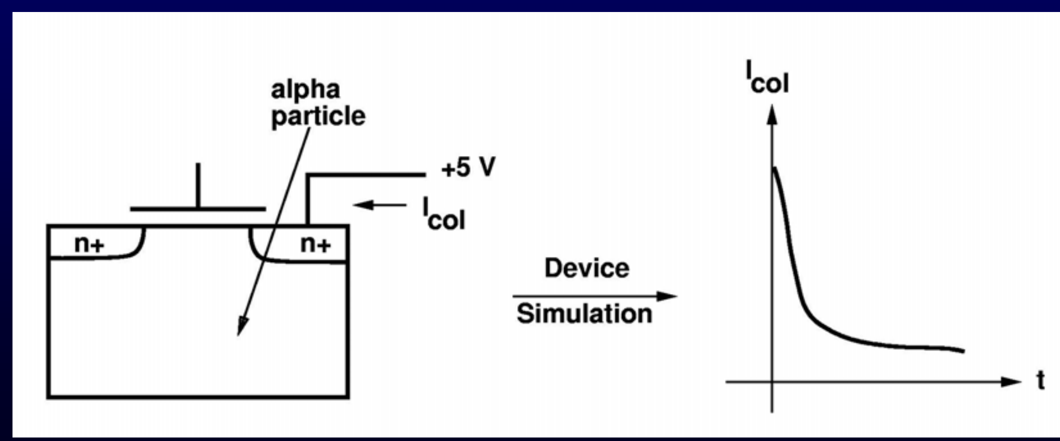
Advantages

- **Simulate critical devices at the device level within a circuit**
  - Solve partial differential equations describing devices coupled to a circuit simulator
- **Predict performance of circuits in absence of compact models for devices**
- **Evaluate influence of process variations on circuit performance**

Application Example – Single Event Upset in SRAM Cell

- **Critical transistor modeled at the physical (numerical) level**
- **Other transistors modeled with compact models**
- **Alpha particle strike simulated with circuit boundary conditions**





Simulation of Micro/Nano Systems

- **Micro/nano device simulation**
  - Finite-element methods (FEM)
  - Fast integral methods
- **Simulation of complete systems**
  - Lumped equivalent circuit representations
  - Macromodels derived from FEM analysis
  - Analog hardware description language (AHDL) descriptions

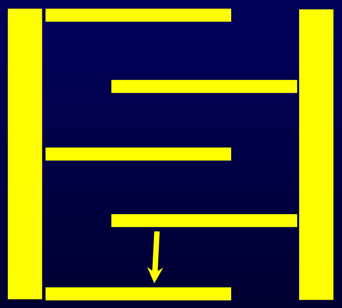
Limitations of High-Level Models

- **Typically derived for small-signal conditions**
- **Not suitable for systems with feedback**
- **Cannot predict behavior outside range**

Beam bending

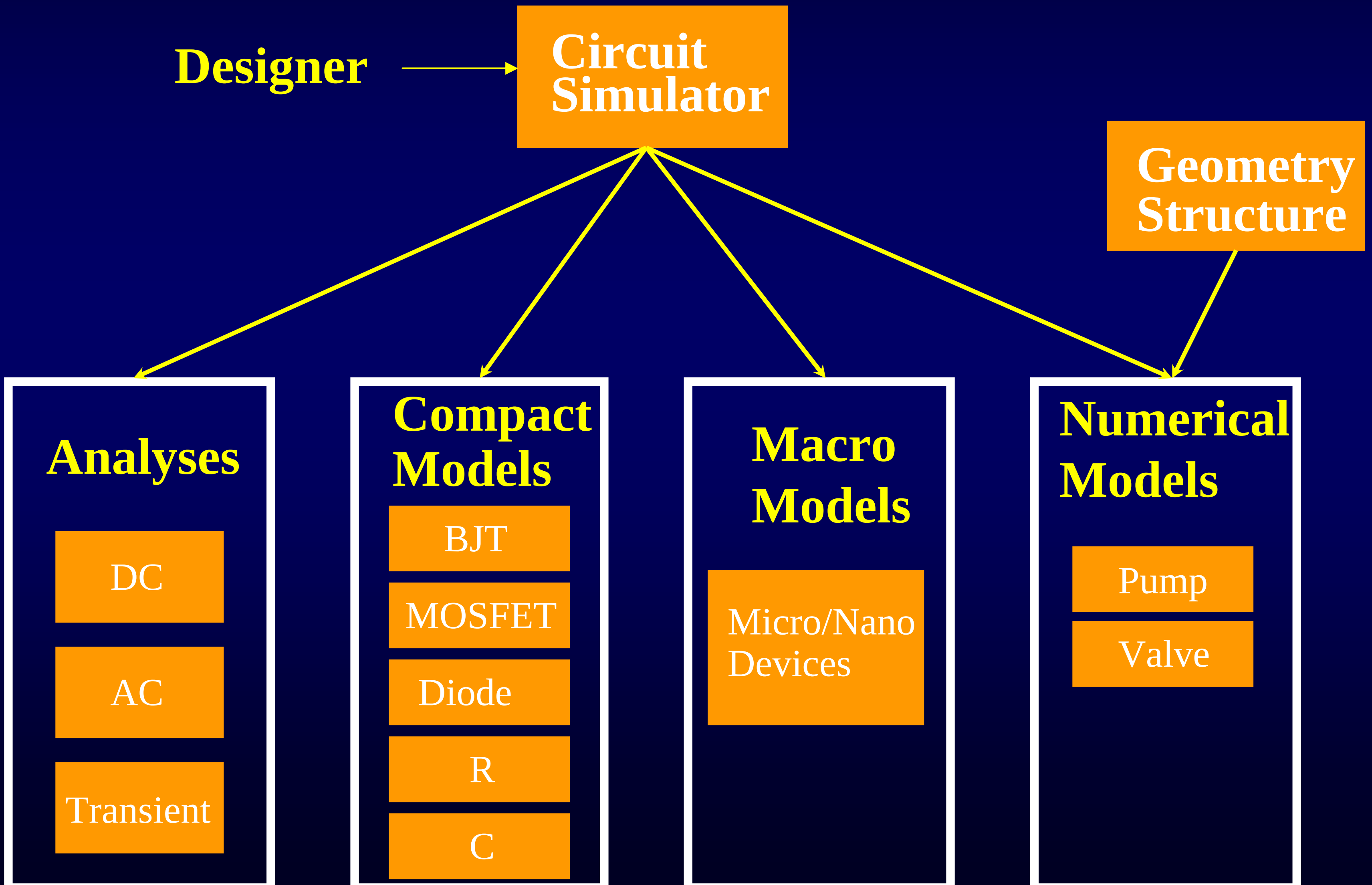
reach substrate

Comb structure



reach limit stops

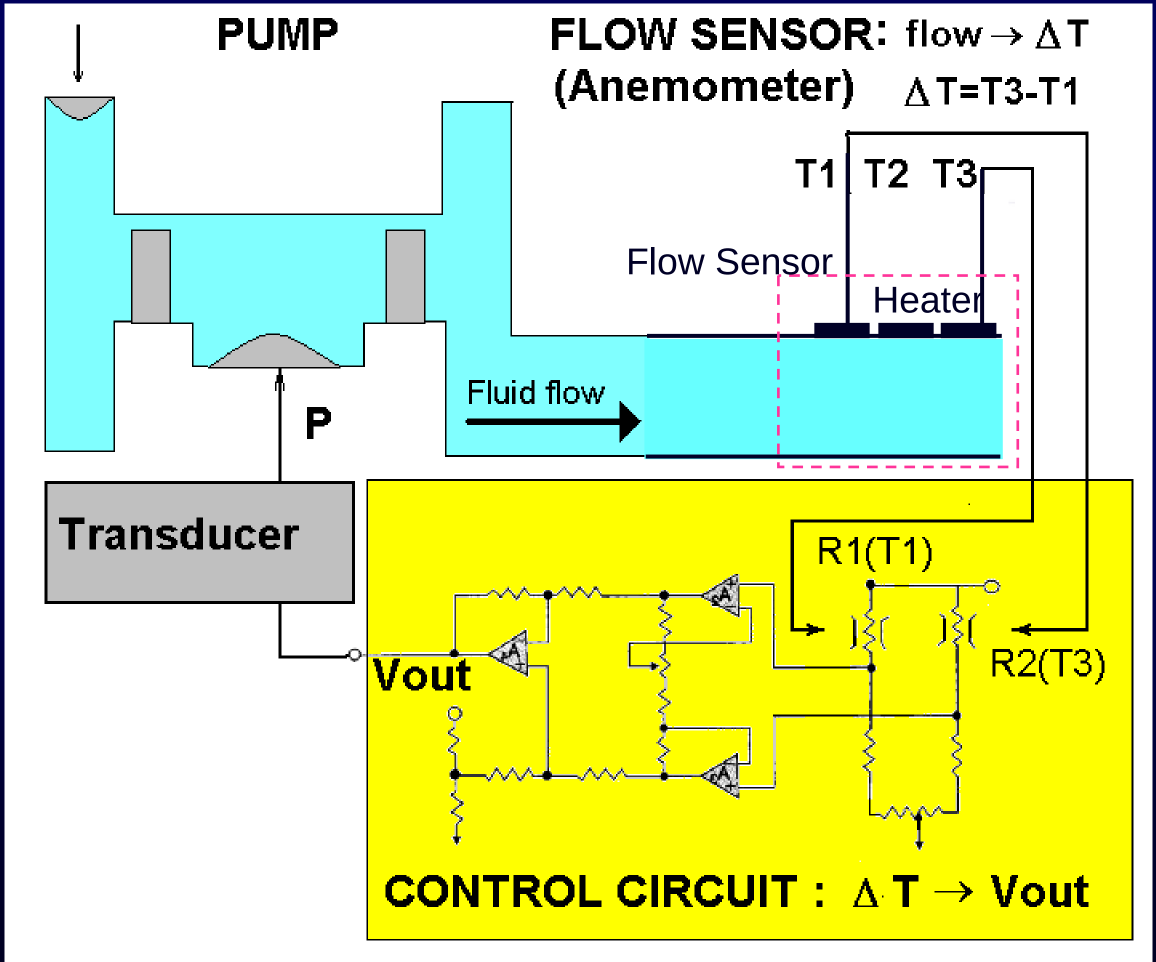
Coupled Circuit/Micro(Nano) Device Simulator



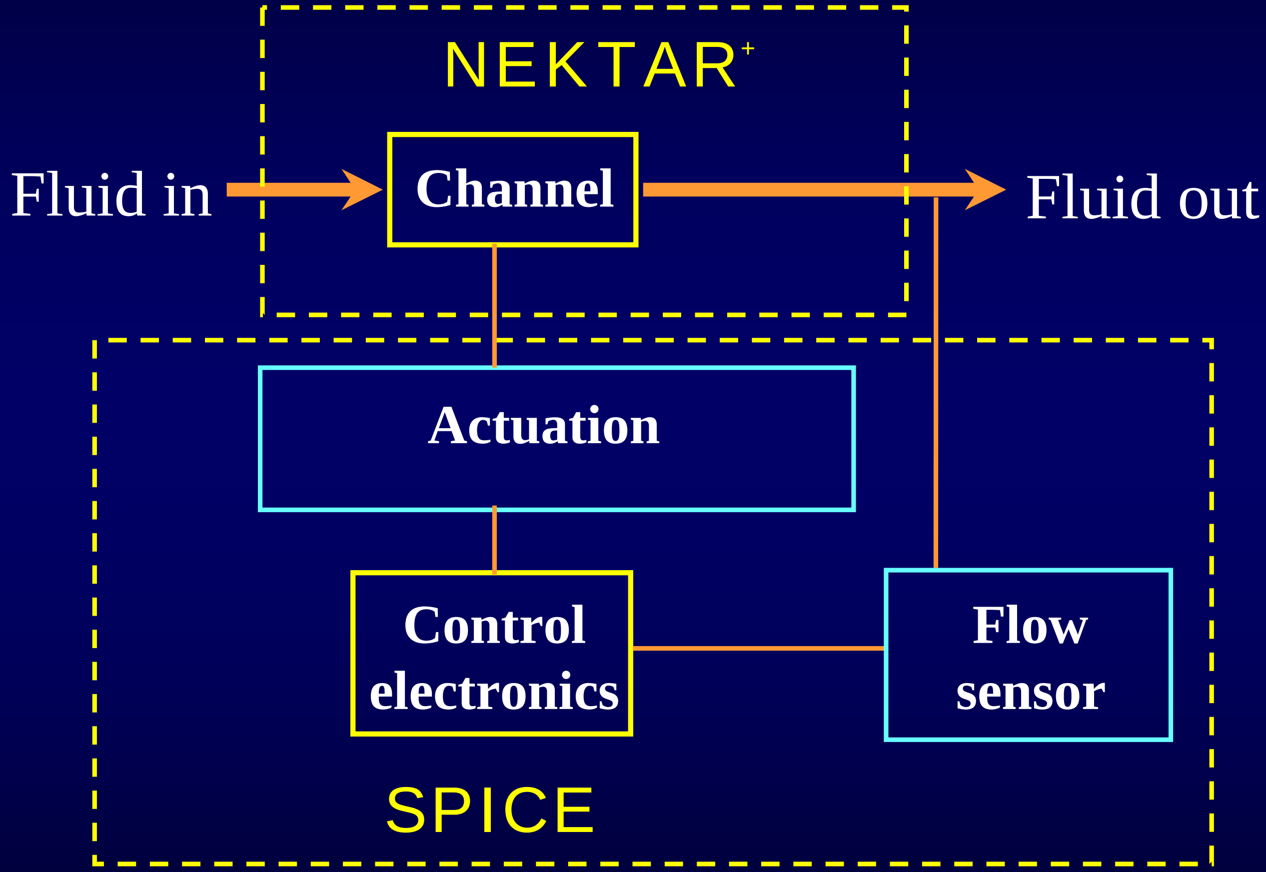
Microfluidic System

Micro Fluidic Simulation Example

- **Constant flow system**



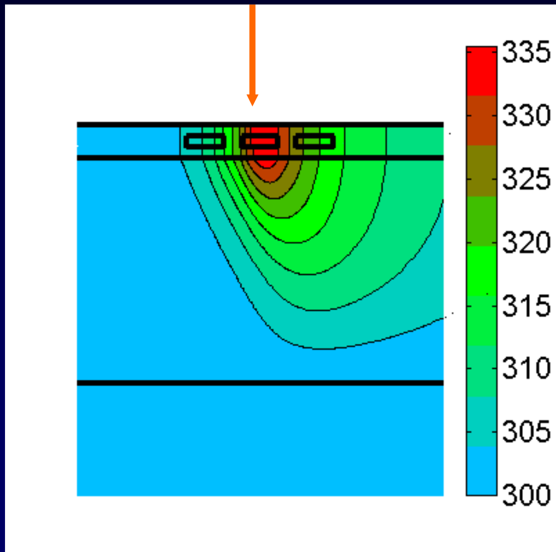
Simulator Interaction



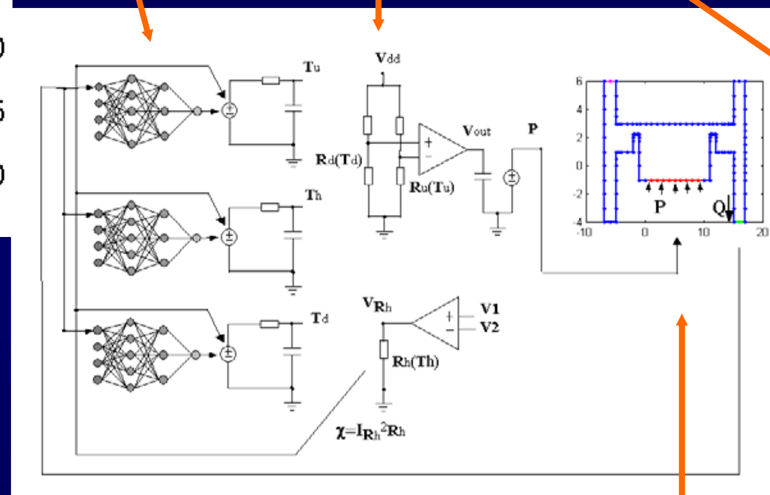
+ R. M. Kirby, et al., “The NEKTAR code: Dynamic simulations without remeshing,” *Proc. ICCT,* 1999.

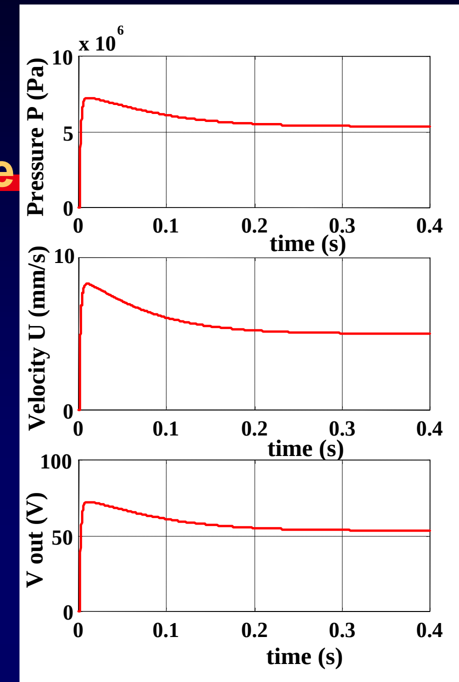
Coupled System Simulation: 4 Physical Domains

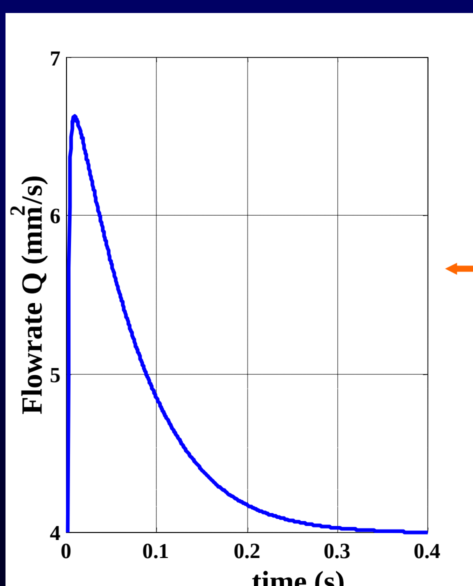
Flow sensor: Flow to Temperature (thermal domain)



Circuit: Temperature to Voltage (electrical domain)

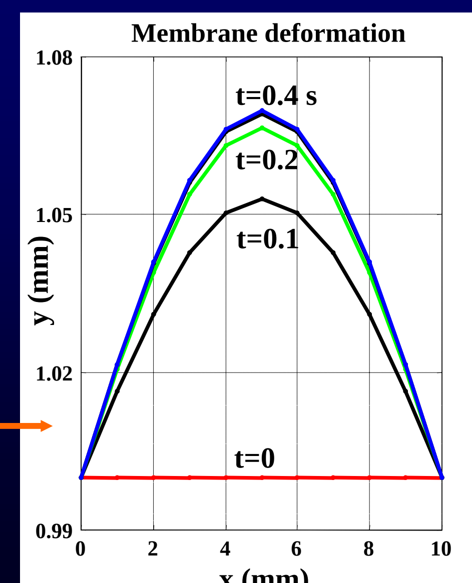






Micropump: Displacement to Flow (fluid domain)

Piezo-actuator: Voltage to Displacement (structure domain)



Summary of Microfluidic System Simulator

- **Integrated simulator allows simulation of complete system with integrated thermal, flow, structural, and electric domains**
- **Fluid solver determines overall simulation performance**

R. M. Kirby, et al., "An integrated simulator for coupled domain problems in MEMS," *JMEMS*, pp. 379-391, Sept. 2001.

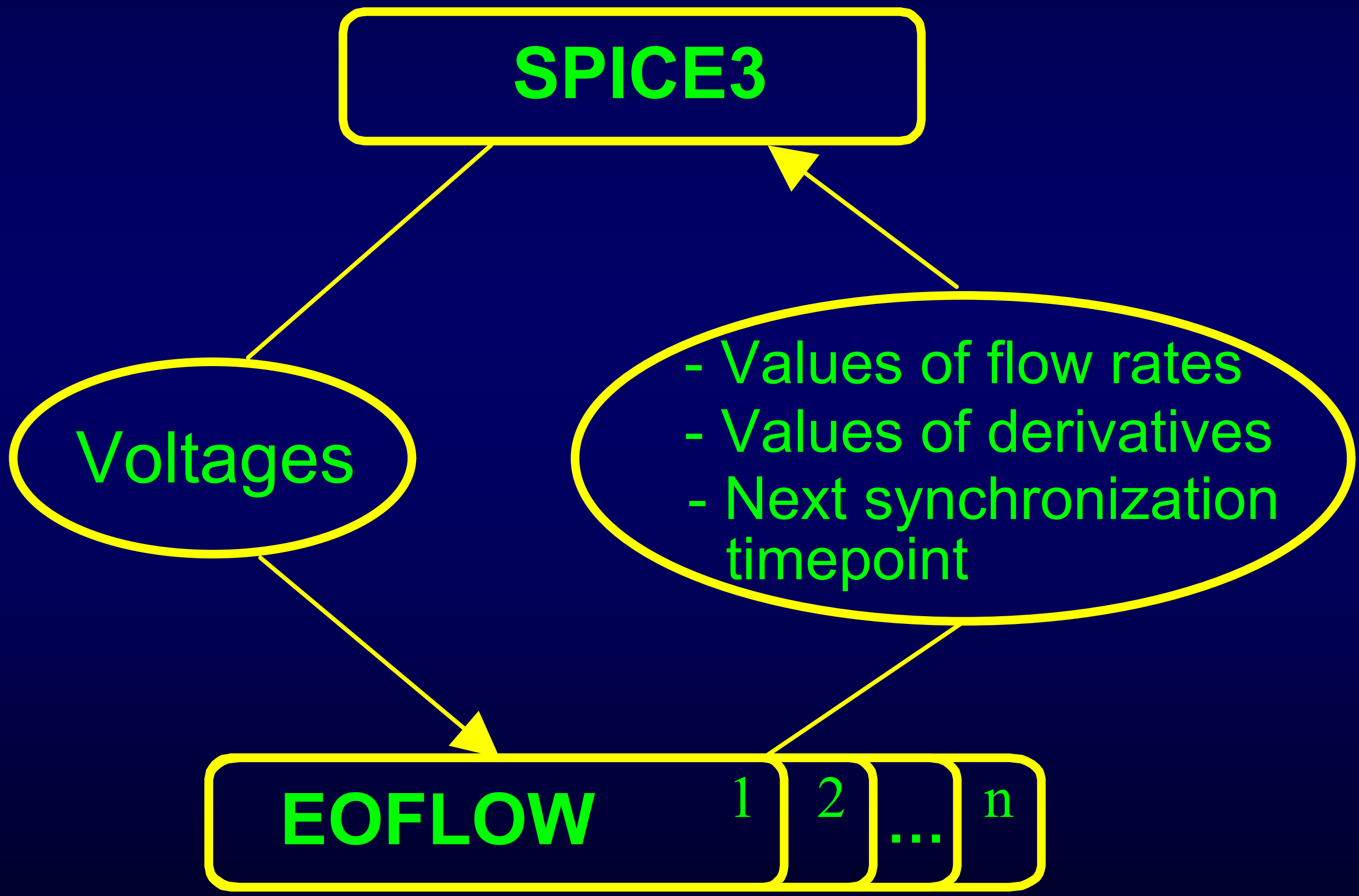
Electroosmotic Flow

Simulation of Electroosmotic Flow

- **An electroosmotic flow channel has fluidic and electronic components**
- **Physical model generation for fluidic channels requires significant time**
  - SPICE3 for circuit-level simulation
  - EOFLOW* for numerical simulation of electroosmotic flow channels

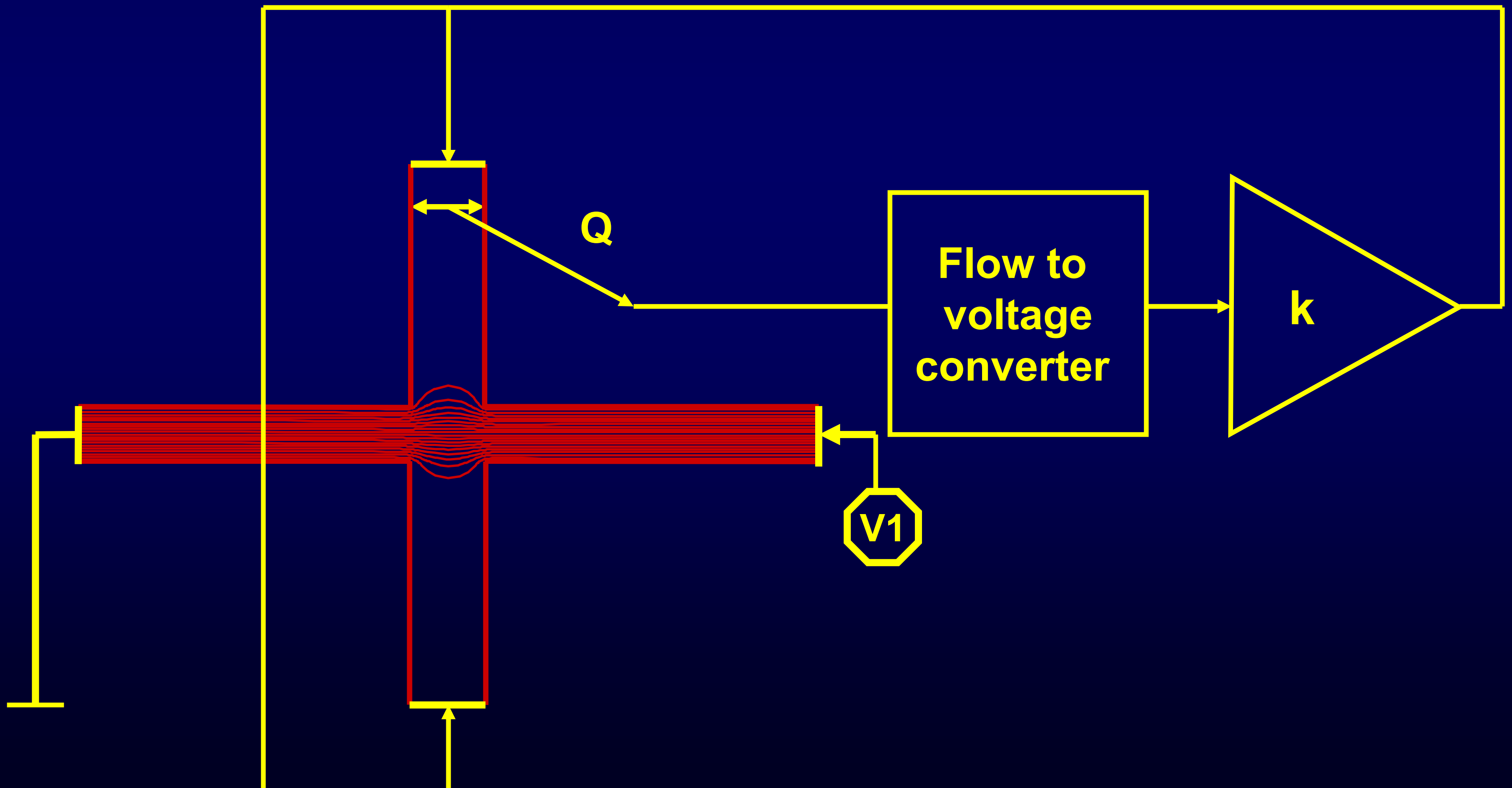
* M. J. Mitchell, et al., "Meshless analysis of steady-state electro-osmotic transport," *JMEMS*, pp. 435–449, Dec. 2000.

Simulator Interaction

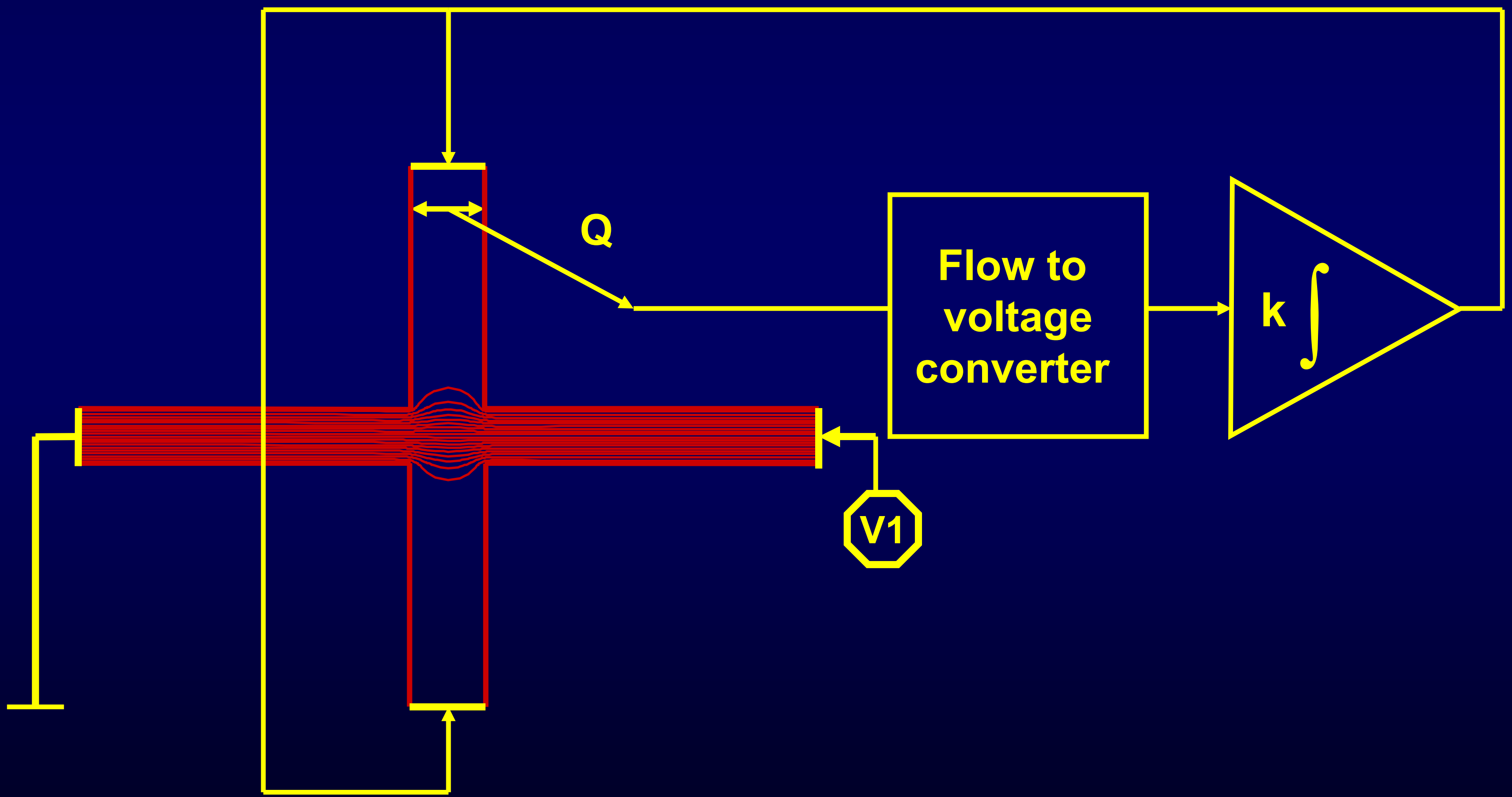


Flow Rate Control System

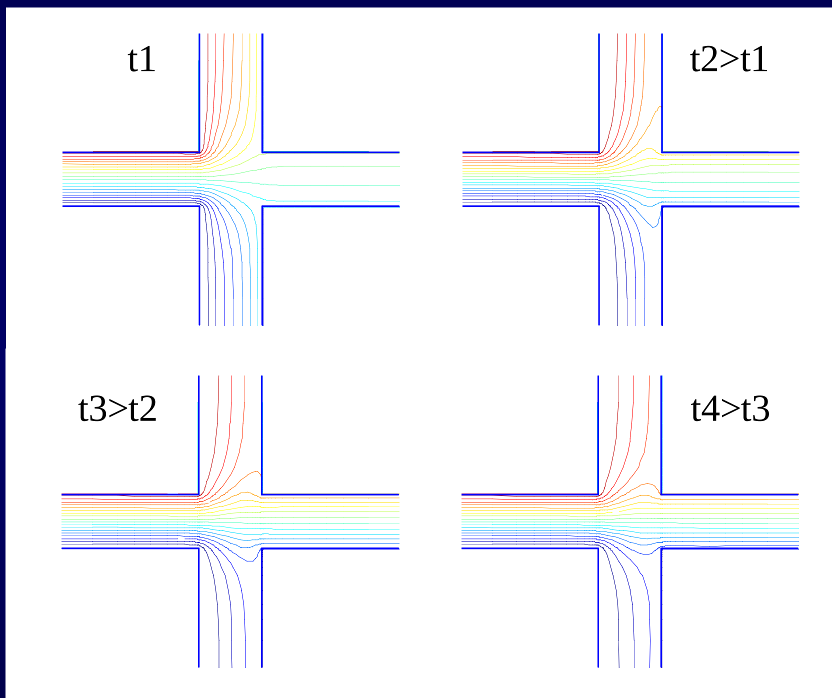
- **To avoid flow distortion, vertical velocity must be reduced**

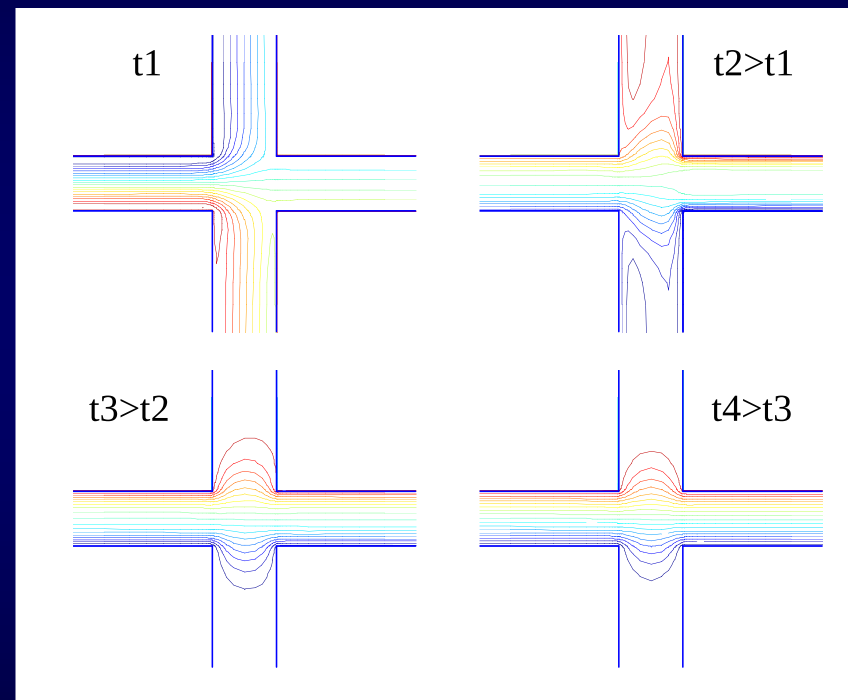


Proportional Integral Control System



Dynamic Behavior of Streamlines for the Electroosmotic System

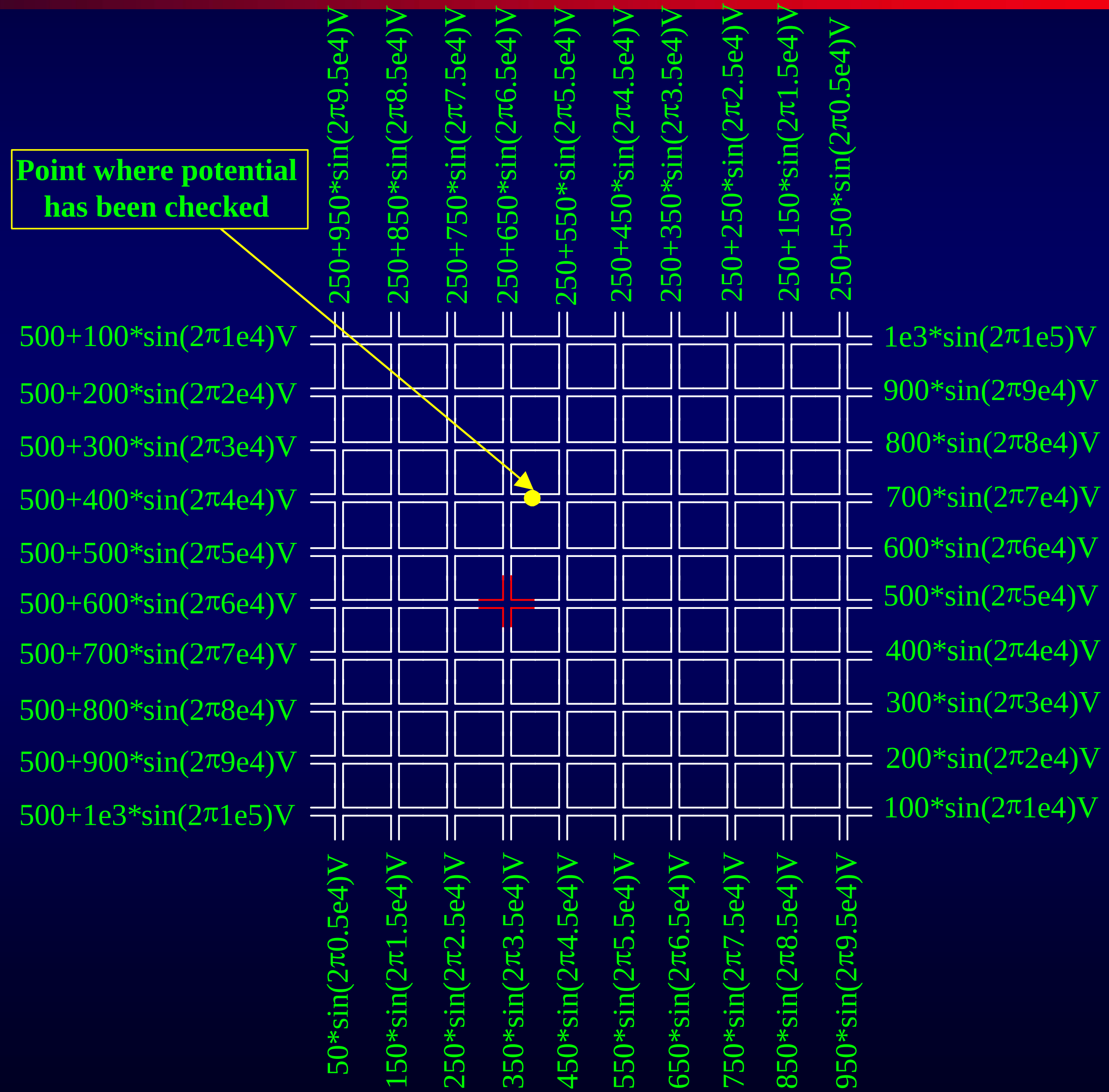




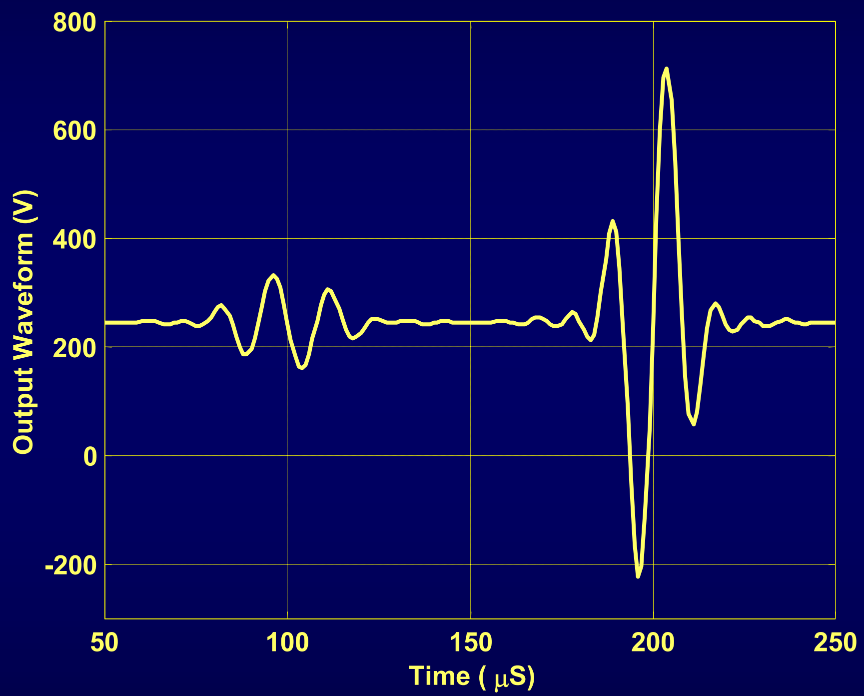
Proportional control

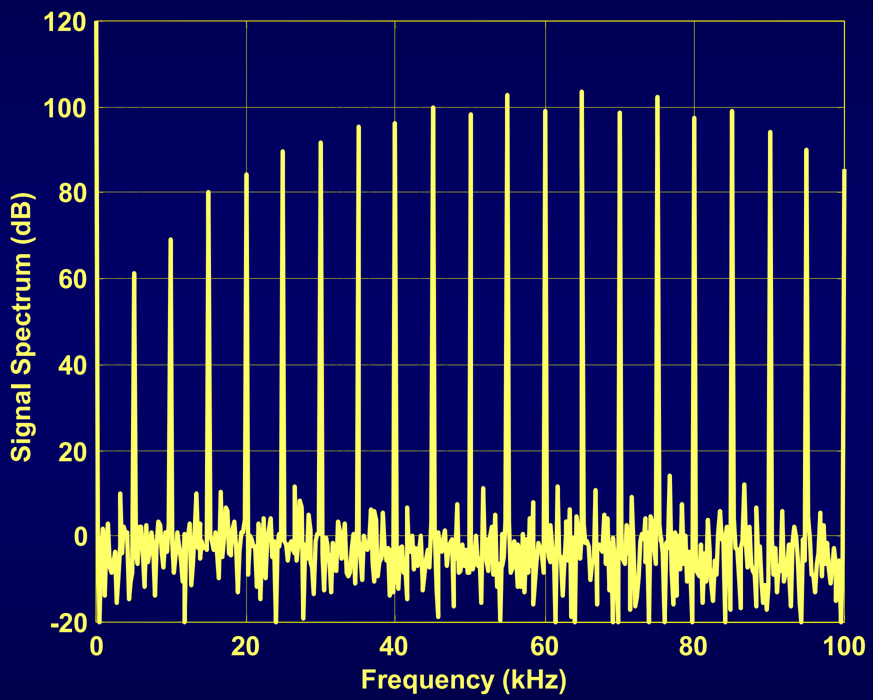
Proportional-integral control

Simulation of a 10 x 10 Cross Channel Mesh



Simulation Results for 10 x 10 Cross Channel Mesh





One period of output signal

Spectrum of output signal

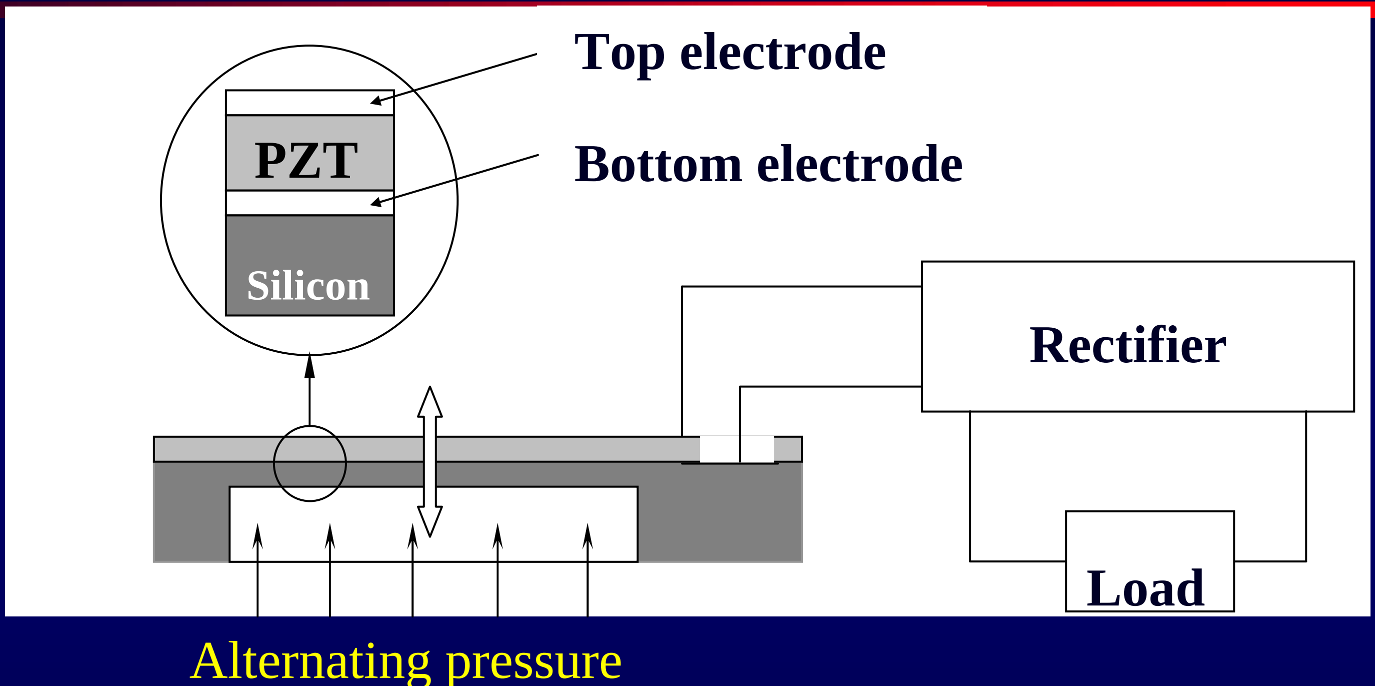
Summary of Electroosmotic Flow Control Simulator

- **Various electronic control options can be evaluated**
  - Proportional-integral control is better than proportional control
- **Simulation of a complex network of interconnected channels possible**

T. Dudar, et al., “Simulation of electronic control in electroosmotic flow channels,” *SISPAD 2003*, pp. 235-238, Sept. 2003.

Piezoelectric Micropower Generation System

Piezoelectric Generator



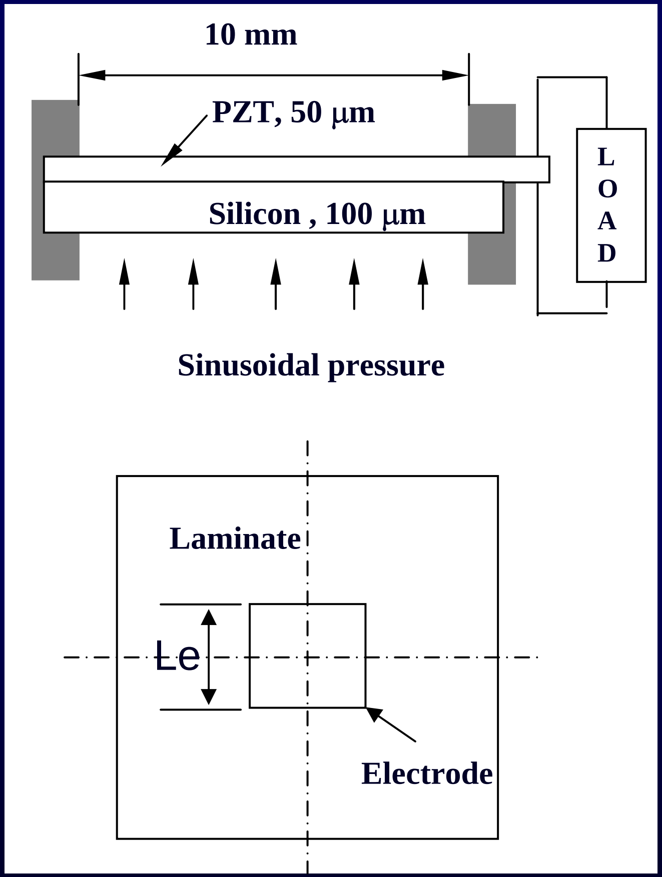
- Mechanically force the membrane to vibrate
- PZT transform mechanical energy into electric energy

C. D. Richard, et al., “MEMS power: The P3 system,” *Proc. IECE2001*

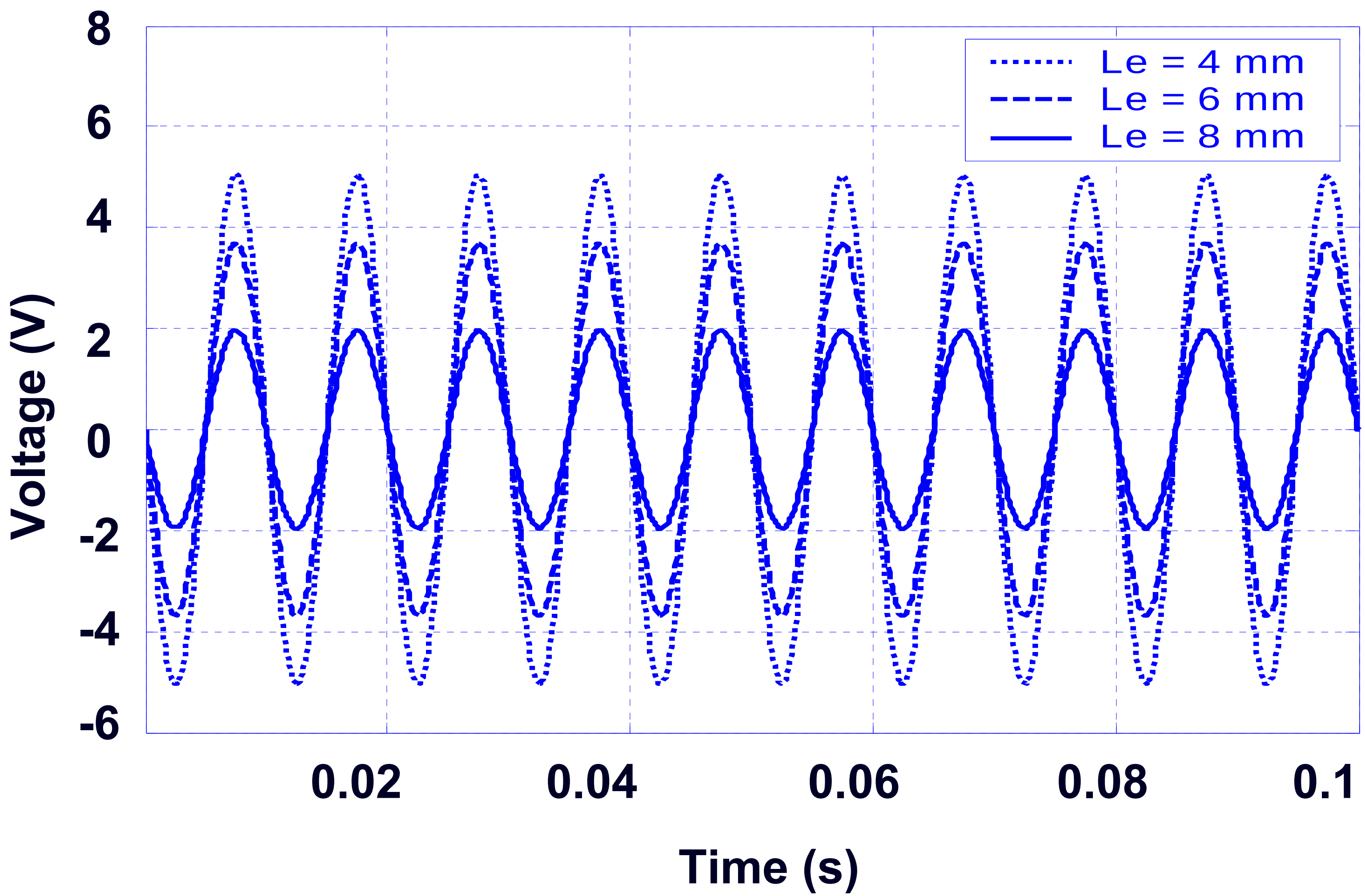
Numerical Example

- The electrode is taken as an equal potential region
- A sinusoidal pressure is applied
- Output voltage depends on electrode length Le
- Power delivered varies with load

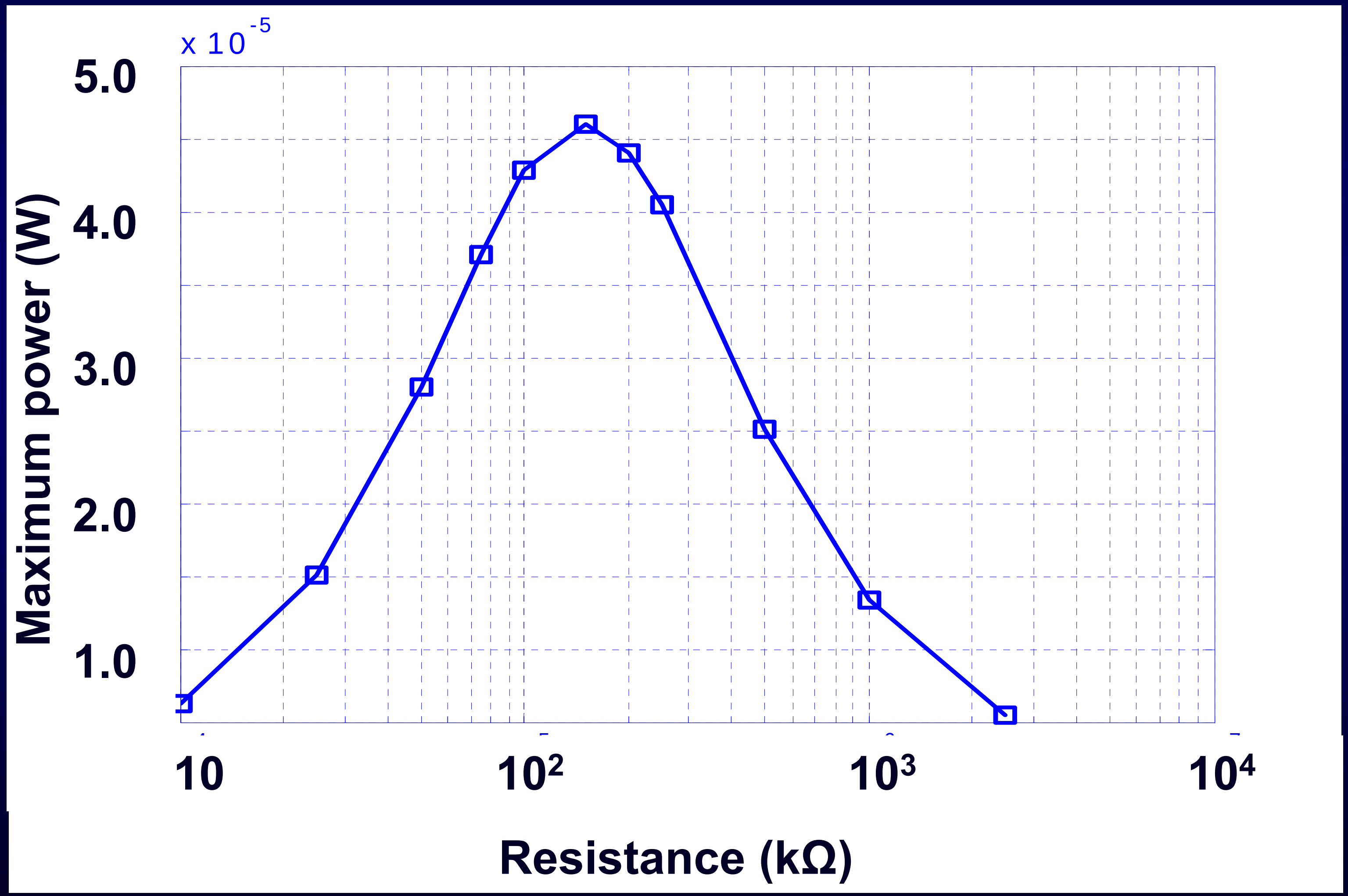
Micro piezogenerator



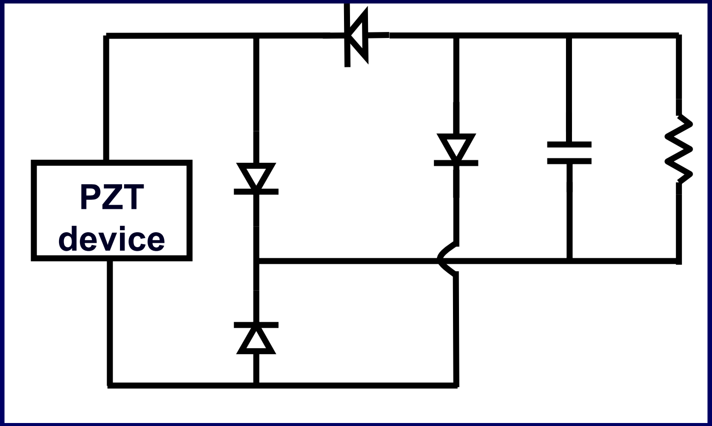
Open Circuit Voltage Decreases With An Increasing Electrode Size



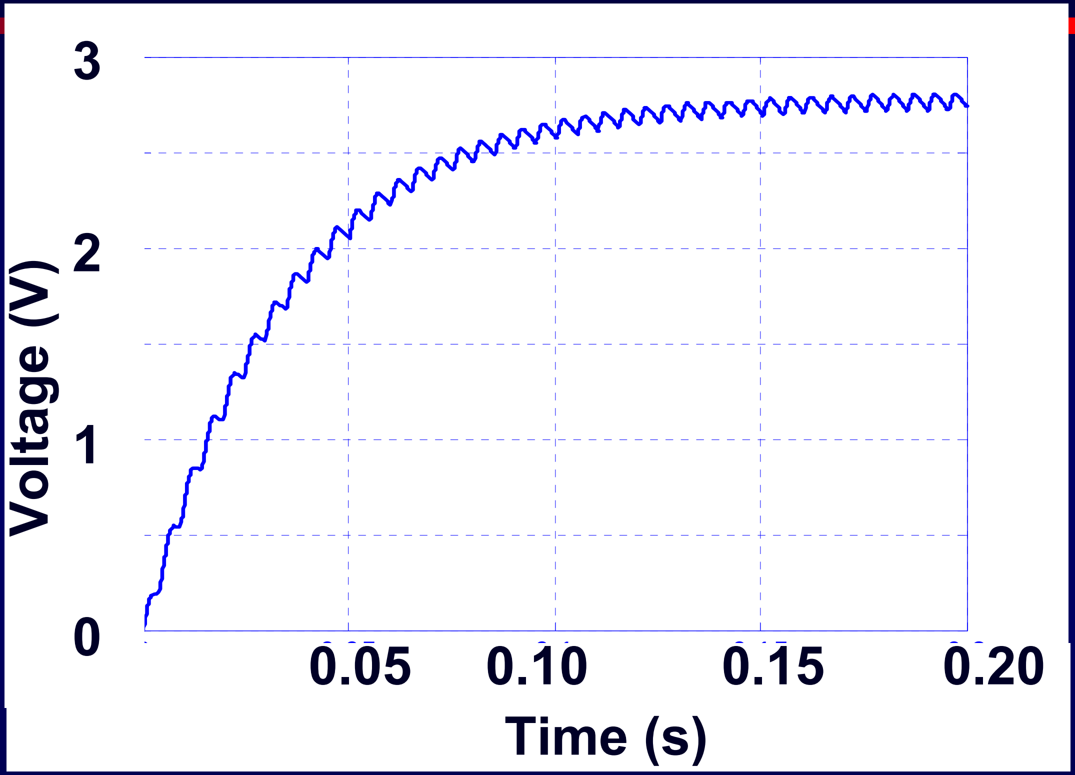
Matching Resistance for maximum power output



A Rectifier Circuit



Circuit Configuration



- The time evolution of the voltage across the load resistor is as expected

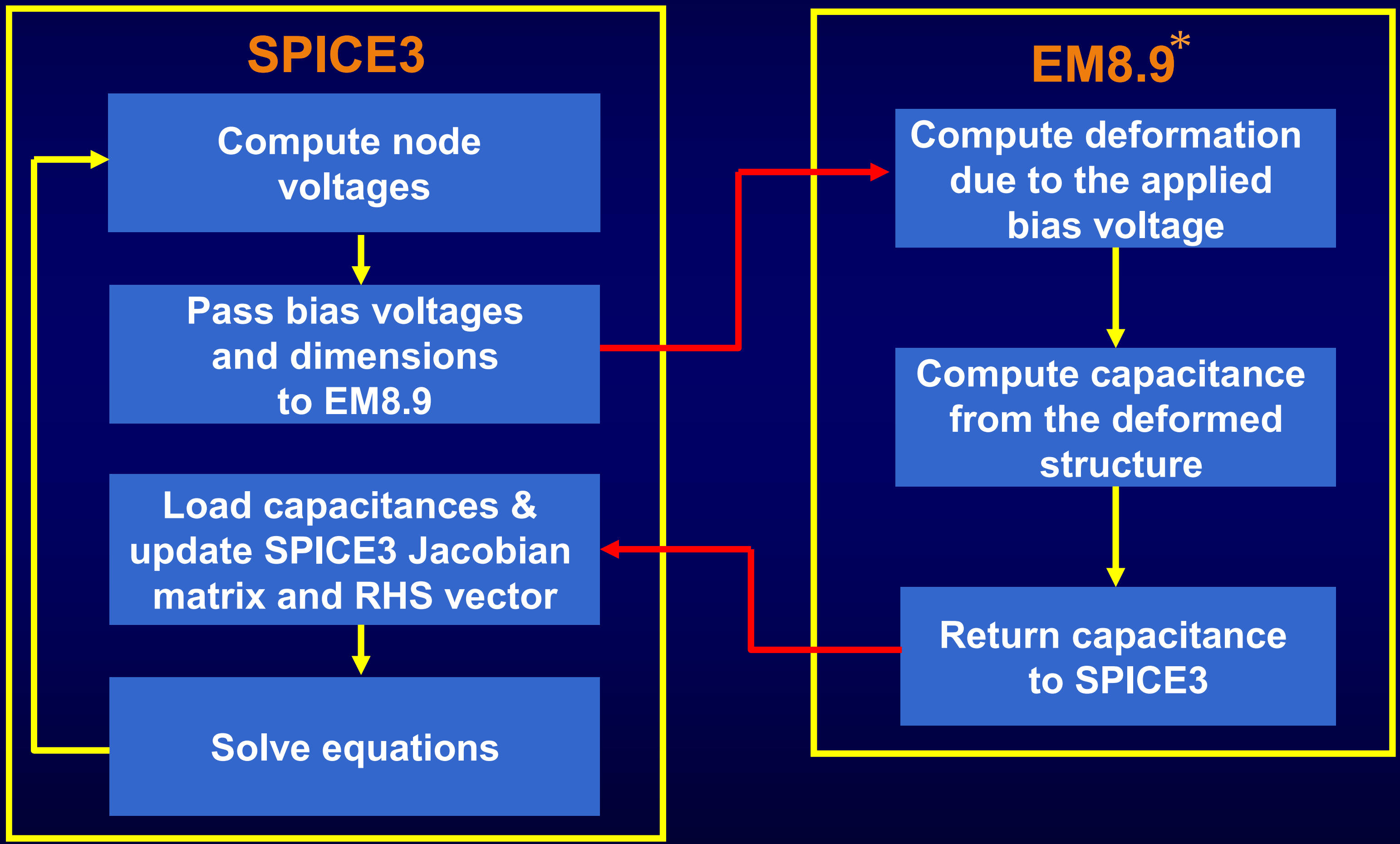
Summary of Piezoelectric Generator Simulator

- **Simulation of coupling piezoelectric devices and complex circuits**
- **Numerical examples demonstrate effectiveness of the coupled simulator**

C. Xu, et al., "Coupled simulation of circuit and piezoelectric laminates," *ISQED 2003*, pp. 369-372, March 2003.

RF MEMS VCOs

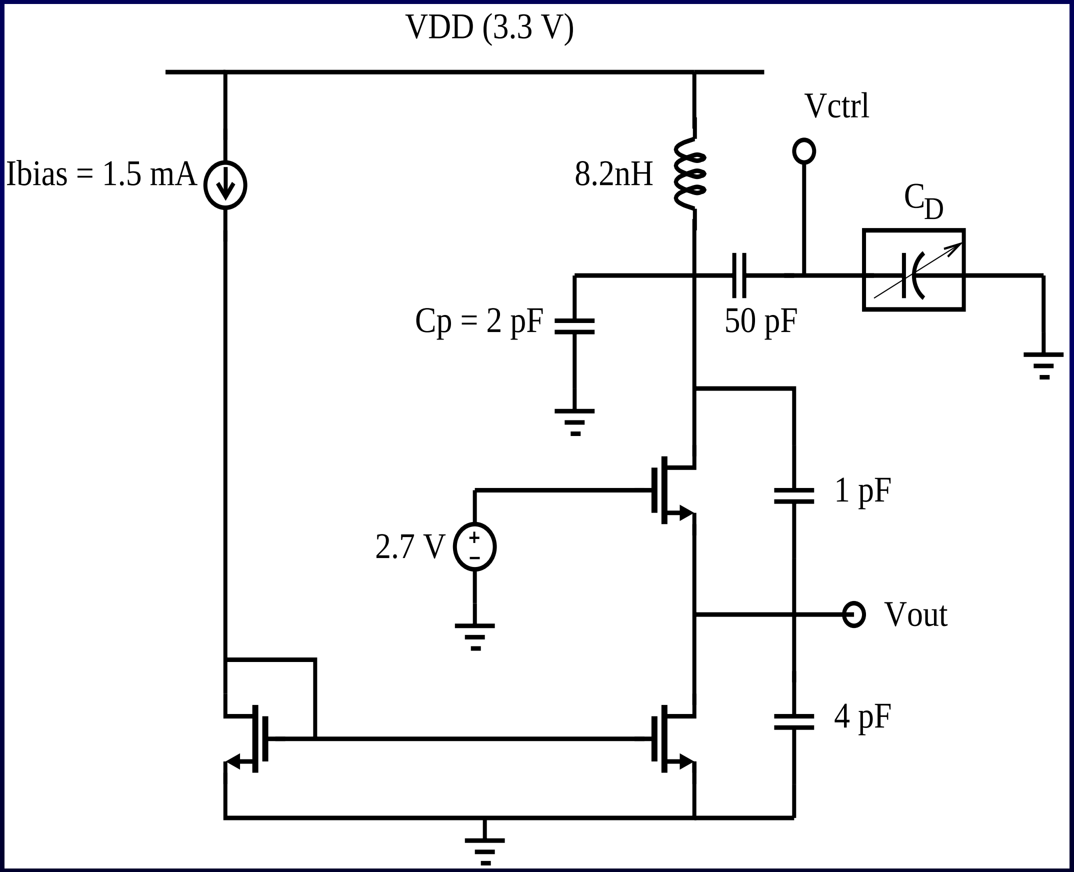
SPICE3 – EM8.9 Integration



* G. Li et al., “Efficient mixed-domain analysis of electrostatic MEMS,” *IEEE Trans. CAD*, pp. 1228-1242, Sept. 2003.

800 MHz MEMS VCO

- **HP 0.8 µm process**

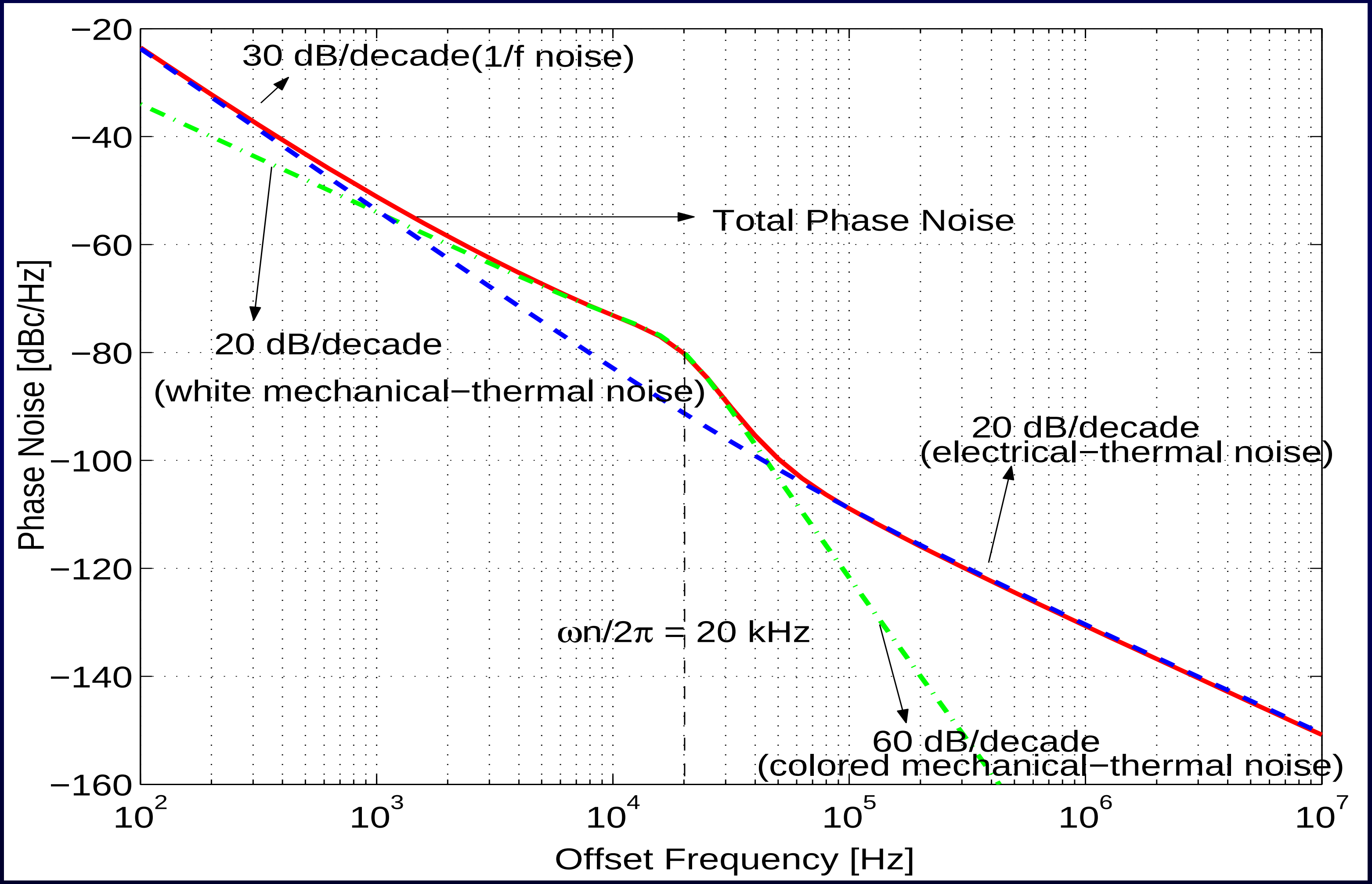


D. J. Young, *Ph.D. Dissertation*, Univ. of California, Berkeley, 1999

Noise Sources in RF MEMS VCOs

- **Electrical-thermal noise**
  - Due to thermal excitation of charge carriers
  - White power spectral density
- **Flicker noise**
  - 1/f noise
- **Mechanical-thermal noise (Brownian noise)**
  - Due to thermal vibration of suspended plates
  - White power spectral density for low offset frequencies and colored for higher frequencies

Simulated Phase Noise



Comparison with Measured Data

Offset Freq.	Measured† ($Q_M = 1$)	Simulated ($Q_M = 1$)	Simulated ($Q_M = 5$)	Simulated ($Q_M = 15$)
10 kHz	-----	-73.1	-77.6	-80.4
100 kHz	-110	-108.9	-109.1	-109.1
3 MHz	-139	-140.8	-140.8	-140.8

† **D. J. Young, *Ph.D. Dissertation*, UC Berkeley, 1999.**

Summary of SPICE3/EM8.9 Simulator

- **Coupled SPICE3/EM8.9 simulator used for accurate simulation of RF MEMS VCOs**
- **Simulated results show the effect of the mechanical quality factor on phase noise**

M. Behera, et al., "Accurate simulation of RF MEMS VCO performance including phase noise," *JMEMS,* April 2005.

Conclusions

- **Coupled circuit/device simulations**
  - Allow accurate simulation of circuits/systems
  - Provide direct link between technology changes and circuit performance
  - Useful for developing accurate compact models
- **Need faster solution methods for PDEs**
- **Different coupling algorithms need to be developed for various problem domains**

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