Silicon Bio-Chips

RF Integrated Electronics

Donhee Ham

DEAS, Harvard University
Silicon Microelectronics

Intel Pentium chips

- contain $\sim 10^8$ MOSFETs
- with size as small as 90 nm.
- operate at GHz speeds.

CMOS microfabrication technology

- Deep submicron resolution lithography
- Moore’s Law
CMOS Chips are everywhere.

- Microprocessors
- Digital signal processors
- Mixed-signal processors
- Analog signal processors
- Why not in Bio?
CMOS / Microfluidic Hybrid for Cell Manipulations

Hakho Lee
(Westervelt Group)

Yong Liu
(Ham Group)

ISSCC 2005

Support:
NSF, IBM, Samsung, Agilent, & Sonnet
IC / Microfluidic Hybrid

Lee et al, ISSCC 2005.
Magnetic-Bead-Bound Cells

Bovine capillary endothelial cells with engulfed magnetic beads.

Lee et al, ISSCC 2005.
Advantages

- Programmable,
- Simultaneous manipulation of individual cells,
- Accurate spatial control,
- Miniaturized and automated,
- Low cost,
- Potential biological applications?
The 1st IC Prototype (SiGe)

Chip size 1mm × 4mm

Lee et al, ISSCC 2005.
IC / Microfluidic Hybrid Prototype

Lee et al, ISSCC 2005.
Magnetic Bead Manipulation

Lee et al, ISSCC 2005.
Biological Cell Manipulation

Bovine capillary endothelial cells with engulfed magnetic beads.

Lee et al, ISSCC 2005.
The 2nd IC Prototype (CMOS)

2 mm × 5 mm

Large array of coils
Logic/timing circuits
Temperature sensors

TSMC 0.18 μm

Yong Liu and Hakho Lee (Equal contribution)
System Architecture

Yong Liu and Hakho Lee (Equal contribution)
Single Bead Manipulation

Hakho Lee and Yong Liu
Multiple Bead Manipulation

20 µm

Hakho Lee and Yong Liu
Artificial Microtissue Assembly

(a) Protein patterning on the surface of the device for cell adhesion

(b) A sheet of cell formed on the surface

(c) Magnetic manipulation of bead-bound cells using a microcoil array

(d) Artificial tissue from heterogeneous cells

Collaborators: Profs. R. M. Westervelt and K. K. Parker
Silicon Bio-Chips

RF Integrated Electronics

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DEAS, Harvard University
**EM Spectrum**

- 300 MHz
- 3 GHz
- 30 GHz
- 300 GHz
- 3 THz

- 100 cm
- 10 cm
- 1 cm
- 1 mm
- 100 μm

**Microwaves**

**mm waves**

**Sub-mm waves**

**Device Technology**

- **Si – CMOS “RF IC”**
- **III-V Compound Semiconductor (GaAs, InP) “MMIC”**
- **Nanoscale devices (e.g. Carbon nanotubes)**
Some RF chips we built in the past.
Self-Sustained Standing Wave Oscillator

William Andress and Donhee Ham

VLSI 2004, RFIC 2004 (Invited)
ISSCC 2004, JSSC 2005

Support: NSF, IBM, ADI, Agilent, AnSoft, Sonnet, & Samsung
Current at $z = 0$ is not exactly zero due to the loading by transistors. 

$\lambda/4$ SWO

Metal width ($w$) and metal spacing ($s$) → Design parameters.

- Increasing $w$ → Lowers $R$ but increases $G$.
- Increasing $s$ → Lowers $R$ but increases $G$.

$R - G$ tradeoff → Constraint in CPS loss minimization.
SW Adaptive CPS Tapering

Minimize $G$

Minimize $R$

Tapered CPS

SW Adaptive CPS Tapering


\[ z = l \]
CPS Tapering in $\theta$-Domain

$P_{diss} = \int_{0}^{l} \left[ \frac{1}{2} R(z) I^2(z) + \frac{1}{2} G(z) V^2(z) \right] dz$

$\theta(z) = \omega \int_{0}^{z} \sqrt{L(z)C(z)} dz \quad z - \theta$ transformation

$P_{diss} = \int_{0}^{\frac{\pi}{2}} \left[ \frac{1}{2} (I_0 \sin \theta)^2 R_\theta(\theta) + \frac{1}{2} (V_0 \cos \theta)^2 G_\theta(\theta) \right] d\theta$

Prediction via EM Simulation

Optimum tapered line:
When hosting standing waves,
Simulated effective $Q \sim 60$

50 % improvement

Optimum uniform line:
Simulated intrinsic $Q \sim 40$

\( \frac{\lambda}{4} \) CMOS SWO Prototypes

- Uniform line SWO
- Tapered line SWO

- RF probe pads
- Floating metal strips

TSMC 0.18\(\mu\)m CMOS

Measurements

<table>
<thead>
<tr>
<th>SWO type</th>
<th>Uniform</th>
<th>Tapered</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN (dBc/Hz) (@1MHz)</td>
<td>-102</td>
<td>-110</td>
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</table>

Vdd = 1.8 V
Icore = 2.6 mA
Electrical Soliton Oscillator

David Ricketts, Xiaofeng Li, Matt DePetro, and Donhee Ham

IMS 2005

Support: ADI, NSF, IBM, Agilent, Sonnet, & Samsung
Solitary Waves, or “Soliton”

(1) A unique class of pulse-shaped waves that propagate in a nonlinear-dispersive medium with unchanged waveforms.

(2) Solitons have been studied over 100 years in various disciplines including CMP, optics, and electronics.
Nonlinear Transmission Lines (NLTL)

• NLTL has been studied for decades.
Solitons on the NLTL

Cnoidal wave (Soliton pulse train)

Mono pulse case

Pulse break-up

Nonlinear collision
Ring NLTL & Soliton Oscillator

Ricketts et al, IMS 2005.
Instability Issues (1)

Signal saturation reduction is needed.

Ricketts et al, IMS 2005.
Instability Issues (2)

Perturbation rejection is needed.

Ricketts et al, IMS 2005.
## Instability Issues - Summary

<table>
<thead>
<tr>
<th></th>
<th>$V_Y$</th>
<th>$V_X$</th>
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<tr>
<td><strong>Saturation Reduction</strong></td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td><strong>Perturbation Rejection</strong></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><strong>Single Mode Selection</strong></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Ricketts *et al*, *IMS* 2005.
Operating Principles

Board-Level Prototype

Ricketts et al, IMS 2005.
Experimental Result

Ricketts et al., IMS 2005.
Silicon (CMOS) GHz Version
Test in Progress

Simulation Results

Ricketts
Microwave Soliton Mode-Locked System

Fast saturable absorber (SA) in optics

Fiber in optics

Optical isolator

Soliton mode-locked fiber ring laser in optics.

Ricketts et al, IMS 2005.
Contributors

- **CMOS/Bio**: Hakho Lee, Yong Liu, and Prof. Westervelt
- **SWO**: William Andress
- **Soliton Oscillator**: David Ricketts, Xiaofeng Li, and Matt DePetro.

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