Reaction Pathways in Processing Photons and Students

Tim Anderson
University of Massachusetts
The p-n Junction

Conduction Band | Valence Band
---|---
Before Contact | After Contact
n-type | p-type

Forward bias | Zero bias
\[ V_{Bi} - V_{Fwd} \] | \[ V_{Bi} \]

\[ V_{oc} \] Condition | \[ J_{sc} \] Condition

Light

Energy gap
Steady State Carrier Injection from Side

In the diagram, the steady state carrier injection is shown from the injecting surface with photons ($h\nu$). The graph illustrates the variation of carrier density ($p_n(x)$) as a function of position ($x$) from 0 to $L_p = \sqrt{D_p \tau_p}$ on the left side, and from 0 to $W$ on the right side, where $W$ is the width of the device. The carrier density at the injecting surface ($p_n(0)$) and at the boundary ($p_n(0)$) are highlighted. The right side also indicates that all excess carriers are extracted.
Reactions

\[ O \leftrightarrow e^- + h^+ \]

\[ r_p = k_1 - k_{-1} n p \]

at equilibrium: \( r_p = 0 \)

\[ k_1 = k_{-1} n_o p_0 = k_{-1} n_i^2 \]

\[ r_p = k_{-1} (n_i^2 - np) \]

\[ E \]

Fastest Rate When

\[ E_{A1} = E_{A2} = 1/2 E_A \]
Single Junction Cell

Analysis for a 24%-efficient Si solar cell

Maximum energy collected = $E_{\text{gap}}$

- Unused Photons: 19%
- 31% Loss for Energy above $E_{\text{gap}}$
- $V_{\text{oc}} < E_{\text{gap}}$: 16%
- Fill Factor: 5%
- Other Losses: 5%
- Usable power: 24%
- Other losses:
  - Absorption
  - Collection
  - Reflection
  - Series R
  - Shunts
Most Promising Thin Film Absorber Material

- High optical absorption coefficient: \( \sim 2 \ \mu m \)
- Direct band gap (\( E_g \sim 1.2 \ eV \))
- High radiation resistance
- High reliability
- Lower cost/Watt installed
- 20\% conversion efficiency
- Efficient in low-angle & light
- Flexible substrates possible
- Positive response under concentration

\( \text{Cu(In}_{1-x}\text{Ga}_x\text{Se}_2 \) Solar Cells

- Mo (0.5-1 \( \mu \)m)
  - Sputter
- CIGS (1-2.5 \( \mu \)m)
  - Multiple methods (coevaporation, sputtering, printing, electrodeposition)
- CdS (700 Å)
  - Chemical Bath Deposition
  - Sputter
- ZnO, ITO (2500 Å)
  - Sputter

1 \( \mu \)m 25000X
Approach

Seek CIGS Pathway
High-rate, high-quality, low temperature

Phase Diagrams
Thermodynamic Properties
CIGS Formation Pathways & Kinetics

Pathway Prediction

ThermoCalc
- Equilibria
- G(T,P) database

HT-XRD
- Pathways
- Rates
- Mobilities

DICTRA
- Atomic Mobilities
- Chemical Potentials
Approach to Developing Phase Diagrams

- DATA
- Critical Evaluation, Model Selection & Assessment
- Equilibrium Phase Diagrams

Thermochemical & Equilibrium
- Literature
- Measurements
- EMF, Equilibration
- First Principles
- Estimation

Structure

Bulk & Point Defects

Cu-Ga-In-Se System
- 4 unary sub-systems
- 6 binary sub-systems
- 4 ternary sub-systems

Critical Evaluation, Model Selection & Assessment

Cu-Ga-In-Se System
- 4 unary sub-systems
- 6 binary sub-systems
- 4 ternary sub-systems
Thermodynamics of CIGS
66 solid phase, 20 liquid phase, and 18 gas species Gibbs models

Cu-Ga-In-Se

Cu-Ga-In

Cu-Ga-Se

Cu-In-Se

Ga-In-Se

Cu-Ga

Cu-In

Cu-Se

Ga-In

Ga-Se

In-Se
HT-XRD System

Panalytical Philips X’pert System

- X-ray tube
- Chamber
- PSD
- Kapton/Be window
- Surrounding Heater
- Sample holder
- CW in out
- In Out (N₂)

Graphite Dome
- Selenium powder
- Precursor sample

Selenium powder
- Precursor sample
Temperature Ramp Anneal

CuGaSe_2
Glass
CuSe
GaSe
Glass

CGS (112)

JCPDS
CuSe #34-0171
Cu_2-xSe #06-0680
CuGaSe_2 #35-1100

CGS (220/204)

Cu_2-xSe (111)

CuSe (101,102)
CuSe (006)

2θ

Glass
Isothermal annealing

TEM-EDS

CGS (112)

T = 280 °C

ramp to 500 °C

CuSe (102)

Cu$_2$+Se (111)

T = 300 °C

(t~30 min)

T = 340 °C

T = 370 °C
TEM-EDS Analysis

Glass/GaSe/CuSe Precursor
TEM-EDS Analysis

Glass/GaSe/CGS/CuSe annealed for 30 min, at 300 °C

EDS line scan

CuSe
CGS
GaSe

Cu
Se
Ga

distance (µm)
GaN-based LEDs

- Issues with Solid State Lighting
  - Cost/lumen **too high**, Flux **too low**
  - Topside n-contact limits active area
  - No suitable substrate for GaN
Motivation for GaN on Si

**Advantages**
- Low cost
- Large area
- High quality n- and p- wafers
- High electrical & thermal conductivities
- Potential for device integration
- Easily removed

**Challenges**
- High dislocation density due large lattice mismatch (17%)
- Cracking due to large thermal coefficient of expansion mismatch (56%)
- Polycrystalline GaN due to Si$_3$N$_4$ formation at the interface
Effect of HCl/TMIn and Growth Temperature

Optimal Conditions:
- $T = 600 \, ^\circ\text{C}$
- $\text{HCl/TMIn}=4$
- $\text{V/III}=250$

InN nanorods by H-MOVPE:

HCl/TMIn vs T

Substrate: $\text{c-Al}_2\text{O}_3$
Comparison with Thermodynamic Analysis

Thermal Decomposition

- No growth
- Nanorods growth
- Film growth

Parameters:
- N/In = 7000
- N/In = 3000
- N/In = 1000
- N/In = 500
- N/In = 250
- N/In = 100

Temperature (°C)

HCl/TMIn ratio

Growth

Etch
GaN Growth on Si Using InN Buffer Materials
**LT-GaN Growth on Si Using InN Buffer Materials**

<table>
<thead>
<tr>
<th>Growth T</th>
<th>Cl/III</th>
<th>V/III</th>
<th>Time</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>560 °C</td>
<td>1</td>
<td>2500</td>
<td>1 hr</td>
<td>Columnar Film</td>
</tr>
<tr>
<td>600 °C</td>
<td>4</td>
<td>250</td>
<td>20 min</td>
<td>Nanorods d=250nm</td>
</tr>
<tr>
<td>600 °C</td>
<td>4</td>
<td>250</td>
<td>1 hr</td>
<td>Nanorods d=500nm</td>
</tr>
<tr>
<td>650 °C</td>
<td>5</td>
<td>250</td>
<td>1 hr</td>
<td>Sparse microrods</td>
</tr>
</tbody>
</table>

30 min LT-GaN uniformly covered InN nanorods with voids at the interface.
Thick GaN Growth on Si Using InN Buffer Materials

- Crack-free 20 μm thick polycrystalline GaN film was successfully grown on Si using dense InN nanorods (d = 500 nm) as a buffer material.
Approach to Measurement of Kinetics

**in situ** Probing of Gas Phase Chemistry
- T, C Measurements
- Intermediate Detection

**in situ** Raman Spectroscopy

Custom FEM Reactor Model
- T and C Profiles

Gaussian
- Vibrational Frequencies
- Thermodynamic Properties
- Rxn Parameters and Pathway Screening

DFT Calculations

Experiments

Reactor Modeling
Experimental Apparatus

- CVD reactor interfaced with Raman spectrometer
  - Laser: Nd:YAG (532.08 nm)
  - Double additive monochromator (grating: 1800 lines/mm)
  - Detectors – photomultiplier tube (PMT) or charge coupled device (CCD)
Gas Phase Chemistry in N$_2$

\[
\begin{align*}
\text{NH}_3 + M & \xrightarrow{} \text{NH}_2 + H + M \\ + \text{TMGa} & \xrightarrow{} \text{DMGa} \xrightarrow{} \text{MMGa} \xrightarrow{} \text{Ga} \\
\text{TMGa:NH}_3 & \xrightarrow{\text{intra molecular}} (\text{DMGa:NH}_2)_x + x\text{CH}_4 \\
\text{TMGa} & \xrightarrow{\text{inter molecular}} \text{DMGa:NH}_2 - \text{TMGa} + \text{CH}_4 + \text{NH}_3 \\
(\text{DMGa:NH}_2)_x + \text{CH}_4 & \xrightarrow{\text{ab initio calculation}}
\end{align*}
\]
$P_T = 1.0 \text{ atm}$
$T_S = 1273 \text{ [K]}$
$V = 3.0 \text{ [cm/s]}$
TMGa-NH$_3$-N$_2$

$P_T = 1.0 \text{ atm}$
$T_S = 1273 \text{ [K]}$
$v = 3.0 \text{ [cm/s]}$
$V/III = 500$

![Graph showing mole fraction of TMGa, TMGa:NH$_3$, and oligomer versus distance from susceptor, with relative Raman intensity on the y-axis.](image-url)
Multiple-Institution Database for Investigating Engineering Longitudinal Development (MIDFIELD)

Longitudinal data (1987/88 – present)

- 883,020 student-level records of all UG students enrolled.
- 100,179 engineering students.
- 6 of the 50 largest U.S. UG engineering programs.
- 12% of all U.S. engineering UG degrees.
- 25% of all U.S. African-American eng. B.S. degrees
## Six Significant Core Courses

<table>
<thead>
<tr>
<th>MATH</th>
<th>PHYSICS</th>
<th>CHEMISTRY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calc 1</td>
<td>Phys 1</td>
<td>Introductory Chem</td>
</tr>
<tr>
<td>Calc 2</td>
<td>Phys 2</td>
<td>Chem 1</td>
</tr>
<tr>
<td>Calc 3</td>
<td>Phys 1 Honors</td>
<td>Chem 2</td>
</tr>
<tr>
<td>Calc 1 Honors</td>
<td>Phys 2 Honors</td>
<td>Chem 1 Honors</td>
</tr>
<tr>
<td>Calc 2 Honors</td>
<td>Phys 1 Lab</td>
<td>Chem 1 Lab</td>
</tr>
<tr>
<td>Calc 3 Honors</td>
<td>Phys 2 Lab</td>
<td>Chem 2 Lab</td>
</tr>
<tr>
<td>Diff Equations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comp. Sci.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**BLUE:** Performance in course was significant to retention
<table>
<thead>
<tr>
<th>Rank</th>
<th>Course</th>
<th>Odds Ratio</th>
<th>95% Wald CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chem 1 Lab</td>
<td>1.590</td>
<td>[1.308, 1.934]</td>
</tr>
<tr>
<td>2</td>
<td>Chem 2 Lab</td>
<td>1.449</td>
<td>[1.182, 1.776]</td>
</tr>
<tr>
<td>3</td>
<td>Chem 1</td>
<td>1.447</td>
<td>[1.287, 1.626]</td>
</tr>
<tr>
<td>4</td>
<td>Calc 2</td>
<td>1.401</td>
<td>[1.228, 1.598]</td>
</tr>
<tr>
<td>5</td>
<td>Calc 1</td>
<td>1.318</td>
<td>[1.138, 1.527]</td>
</tr>
<tr>
<td>6</td>
<td>Phys 1 Lab</td>
<td>1.214</td>
<td>[1.045, 1.412]</td>
</tr>
</tbody>
</table>

All other courses had 95% Wald CIs [<1.0, >1.0] (i.e., not significant)
Student flow among engineering subfields. Values are percentage of students beginning in particular subfields that graduate in any (possibly the same) subfield. Total number of beginning engineering students was 20,728.

<table>
<thead>
<tr>
<th>BEGIN GRAD</th>
<th>Chemical</th>
<th>Civil</th>
<th>Computer</th>
<th>Electrical</th>
<th>Industrial</th>
<th>Mechanical/Aerospace</th>
<th>Other Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical</td>
<td>55.4</td>
<td>1.0</td>
<td>0.4</td>
<td>1.1</td>
<td>0.5</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Civil</td>
<td>2.9</td>
<td>66.3</td>
<td>1.6</td>
<td>2.5</td>
<td>2.6</td>
<td>4.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Computer</td>
<td>0.4</td>
<td>0.2</td>
<td>60.9</td>
<td>1.7</td>
<td>0.2</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Electrical</td>
<td>1.6</td>
<td>1.6</td>
<td>12.5</td>
<td>62.9</td>
<td>1.4</td>
<td>3.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Industrial</td>
<td>5.4</td>
<td>3.1</td>
<td>4.3</td>
<td>4.6</td>
<td>75.6</td>
<td>4.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Mechanical/Aerospace</td>
<td>3.0</td>
<td>3.6</td>
<td>1.8</td>
<td>4.2</td>
<td>2.6</td>
<td>57.7</td>
<td>4.9</td>
</tr>
<tr>
<td>Other Engineering</td>
<td>4.1</td>
<td>2.4</td>
<td>0.2</td>
<td>2.4</td>
<td>0.8</td>
<td>3.9</td>
<td>59.8</td>
</tr>
<tr>
<td>Total</td>
<td>72.8</td>
<td>78.1</td>
<td>81.6</td>
<td>79.5</td>
<td>83.7</td>
<td>75.8</td>
<td>75.5</td>
</tr>
</tbody>
</table>
Student flow from engineering to non-engineering fields. Values are percentage of students beginning in a given subfield that graduate in a given non-engineering discipline. The total number of beginning engineering students was 20,728.

<table>
<thead>
<tr>
<th>BEGIN</th>
<th>Chemical</th>
<th>Civil</th>
<th>Computer</th>
<th>Electrical</th>
<th>Industrial</th>
<th>Mechanical/Aerospace</th>
<th>Other Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biology</td>
<td>4.0</td>
<td>1.0</td>
<td>0.9</td>
<td>1.2</td>
<td>0.5</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Business</td>
<td>4.3</td>
<td>6.0</td>
<td>4.1</td>
<td>4.9</td>
<td>9.4</td>
<td>6.6</td>
<td>5.5</td>
</tr>
<tr>
<td>CIS</td>
<td>0.9</td>
<td>0.6</td>
<td>7.7</td>
<td>3.1</td>
<td>0.7</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Physical Science</td>
<td>8.2</td>
<td>1.0</td>
<td>0.9</td>
<td>0.8</td>
<td>0.4</td>
<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Social Science</td>
<td>1.8</td>
<td>2.3</td>
<td>2.1</td>
<td>2.0</td>
<td>1.2</td>
<td>3.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Other Non-Engineering</td>
<td>8.0</td>
<td>11.0</td>
<td>2.7</td>
<td>8.5</td>
<td>4.1</td>
<td>10.1</td>
<td>11.7</td>
</tr>
<tr>
<td>Total</td>
<td>27.2</td>
<td>21.9</td>
<td>18.4</td>
<td>20.5</td>
<td>16.3</td>
<td>24.2</td>
<td>24.5</td>
</tr>
</tbody>
</table>
Student flow from non-engineering to engineering fields. Values are percentage of students beginning in a given non-engineering discipline that graduate in an engineering subfield. The total number of non-engineering students was 76,960.

<table>
<thead>
<tr>
<th>BEGIN</th>
<th>Biology</th>
<th>Business</th>
<th>CIS</th>
<th>Physical Science</th>
<th>Social Science</th>
<th>Other Non-Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical</td>
<td>0.3</td>
<td>0.1</td>
<td>0.2</td>
<td>2.6</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Civil</td>
<td>0.4</td>
<td>0.2</td>
<td>0.9</td>
<td>0.9</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Computer</td>
<td>0.0</td>
<td>0.0</td>
<td>2.8</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Electrical</td>
<td>0.1</td>
<td>0.1</td>
<td>2.9</td>
<td>1.6</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Industrial</td>
<td>0.5</td>
<td>0.9</td>
<td>1.7</td>
<td>1.2</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Mechanical/Aerospace</td>
<td>0.4</td>
<td>0.2</td>
<td>1.0</td>
<td>1.8</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Other Engineering</td>
<td>0.6</td>
<td>0.3</td>
<td>0.6</td>
<td>2.0</td>
<td>0.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Total</td>
<td>2.3</td>
<td>1.8</td>
<td>10.2</td>
<td>10.3</td>
<td>1.0</td>
<td>2.7</td>
</tr>
</tbody>
</table>
### Pair-Wise Comparisons Among CHE, OENG, SCI and NSCI Groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>Statistic</th>
<th>CHE</th>
<th>OENG</th>
<th>SCI</th>
<th>NSCI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SAT math score</strong></td>
<td>M</td>
<td>645.92a</td>
<td>635.88b</td>
<td>609.11c</td>
<td>533.16d</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>82.29</td>
<td>83.83</td>
<td>96.20</td>
<td>92.20</td>
</tr>
<tr>
<td><strong>SAT verbal score</strong></td>
<td>M</td>
<td>533.96a</td>
<td>517.34b</td>
<td>519.66b</td>
<td>490.06c</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>86.73</td>
<td>87.62</td>
<td>95.66</td>
<td>87.45</td>
</tr>
<tr>
<td><strong>High School GPA</strong></td>
<td>M</td>
<td>3.72a</td>
<td>3.56b</td>
<td>3.57b</td>
<td>3.31c</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.36</td>
<td>0.41</td>
<td>0.47</td>
<td>0.52</td>
</tr>
<tr>
<td>Months to Graduation</td>
<td>M</td>
<td>53.88a</td>
<td>55.90b</td>
<td>51.77c</td>
<td>51.82c</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>8.88</td>
<td>10.24</td>
<td>11.22</td>
<td>10.88</td>
</tr>
<tr>
<td>Cumulative GPA</td>
<td>M</td>
<td>3.17a</td>
<td>2.98b</td>
<td>3.04c</td>
<td>2.97d</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.49</td>
<td>0.55</td>
<td>0.68</td>
<td>0.54</td>
</tr>
<tr>
<td># Major Changes</td>
<td>M</td>
<td>0.63a</td>
<td>0.95b</td>
<td>0.89c</td>
<td>1.29d</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.76</td>
<td>0.83</td>
<td>0.92</td>
<td>1.03</td>
</tr>
<tr>
<td>Semesters to Graduation</td>
<td>M</td>
<td>13.04a</td>
<td>13.87b</td>
<td>11.69c</td>
<td>10.94d</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>4.07</td>
<td>4.35</td>
<td>3.62</td>
<td>2.62</td>
</tr>
<tr>
<td>Cum. Semester Hours</td>
<td>M</td>
<td>163.35a</td>
<td>168.87b</td>
<td>146.05c</td>
<td>136.11d</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>38.42</td>
<td>42.12</td>
<td>36.29</td>
<td>26.10</td>
</tr>
<tr>
<td>Avg. Semester Hours</td>
<td>M</td>
<td>13.01a</td>
<td>12.60b</td>
<td>12.84c</td>
<td>12.68d</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>2.34</td>
<td>2.22</td>
<td>1.99</td>
<td>1.75</td>
</tr>
</tbody>
</table>
Nonparametric Survival Analysis

Class of statistical methods for studying the occurrence and timing of events.
- Originally used to analyze cancer data.
- Engineering literature: reliability or failure time analysis
- Probability of an event occurring at a particular time.

Definitions
- A non-failure: A student who did not leave an engineering major, i.e., graduated with an engineering degree or is still enrolled in eng.
- A failure: A student who left an engineering major, i.e., changed major from engineering to another discipline or left the university.
- A major change from one engineering major to another one at the same institution or student who leaves engineering but returns to engineering at the same institution do not constitute failure.

Examined cognitive factors (SAT, HS GPA, college GPA, individual characteristics (gender and ethnicity), and institutional characteristics (institutional type, size).
Hazard Function by Gender and Ethnicity

Hazard Function Estimates

- Female
- Male

Hazard Function Estimates

- Asian
- Minority
- Other
- White
By SAT Score Group

Hazard Function Estimates

- 200<=SATM <500
- 500<=SATM <550
- 550<=SATM <600
- 600<=SATM <650
- 650<=SATM <700
- 700<=SATM <750

Hazard Rate vs. Semester

- 200<=SATV <=500
- 500<=SATV <=550
- 550<=SATV <=600
- 600<=SATV <=650
- 650<=SATV <=700
- 700<=SATV <=750
- 750<=SATV <=800
GPA Distributions of Students Who Leave in Semester 3 and Those Who Remain
Is GPA a Continuous Variable?

- With fewer credit hours, certain GPAs are more likely
- Effect lasts only 1-2 semesters
Other Studies

- Is there grade inflation?
  - Is it justified?
- Does block scheduling work?
- Variations among institutional setting?
- What is the effect of a ‘wake-up call’?
- What prerequisites are needed?
- Do performance-based scholarships change student behavior?
- What are the best predictors of success?
Contributing Researchers

- **Guili Zhang (UF PhD, Education)**
- **Youngkyoung Min (UF PhD, Education)**
- **Brian Thorndyke (UF PhD Physics)**
- Miguel Padilla (*UF PhD Educational Psychology*)
- **Miguel Padilla (UF PhD Educational Psychology)**
- **Steve Chang (UF Statistics Graduate Student)**
- **Russell Long (Purdue University)**
- **Matthew W. Ohland (Purdue University)**
## COMPARISON BETWEEN a CHEMICAL PROCESSING PLANT and an INTEGRATED CIRCUIT

<table>
<thead>
<tr>
<th>Raw material source</th>
<th>Many but depleting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of species</td>
<td>$10^2$ or more</td>
</tr>
<tr>
<td>Transport</td>
<td>Pipe (10 inch O.D.)</td>
</tr>
<tr>
<td>Storage</td>
<td>Tank ($10^6$ moles)</td>
</tr>
<tr>
<td>Pump</td>
<td>$10$ hp</td>
</tr>
<tr>
<td>Control</td>
<td>Gate valve</td>
</tr>
<tr>
<td>Reactions</td>
<td>Many</td>
</tr>
<tr>
<td>Flow Rates</td>
<td>$10^3$ moles/s</td>
</tr>
<tr>
<td>Unit operations</td>
<td>$10^4$/mi$^2$</td>
</tr>
<tr>
<td>Cost</td>
<td>$10^8$ ($10^9$/mi$^2$)</td>
</tr>
<tr>
<td>Diffusion coefficient</td>
<td>$10^{-2}$ to $10^{-5}$ cm$^2$/s</td>
</tr>
<tr>
<td>Reaction Rate</td>
<td>$10^6$ 1/moles/s</td>
</tr>
</tbody>
</table>

| Electrical ground   |                      |
| 2 (electron, hole)  |                      |
| Wire, metal interconnect | ($10^{-5}$ cm O.D.) |
| Storage             | Capacitor ($10^{-10}$ moles) |
| Pump                | $10^{-9}$ hp (bipolar transistor) |
| Control             | FET                  |
| Control             | Transistor           |
| Reactions           | Recombination/generation |
| Flow Rates          | $10^{-11}$ moles/s   |
| Unit operations     | $10^{18}$/mi$^2$     |
| Cost                | $10^2$ ($10^9$/mi$^2$) |
| Diffusion coefficient | 10 to $10^3$ cm$^2$/s |
| Reaction Rate       | $10^{16}$ 1/moles/s  |
Acknowledgements

- **U.S. Department of Energy** (support through SAI and F-PACE awards)
- **Oak Ridge National Laboratory** *(HTML, CNMS, and SHARE User Program)*
- **NREL** *(R. Noufi)*