Environmental and Manufacturing Metrics in Semiconductor Interconnect Technology

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Objectives

Design-for-Environment (DFE) methodology for assessing & optimizing Environment/Safety/Health (ESH) impact metrics from the science plane to the factory level

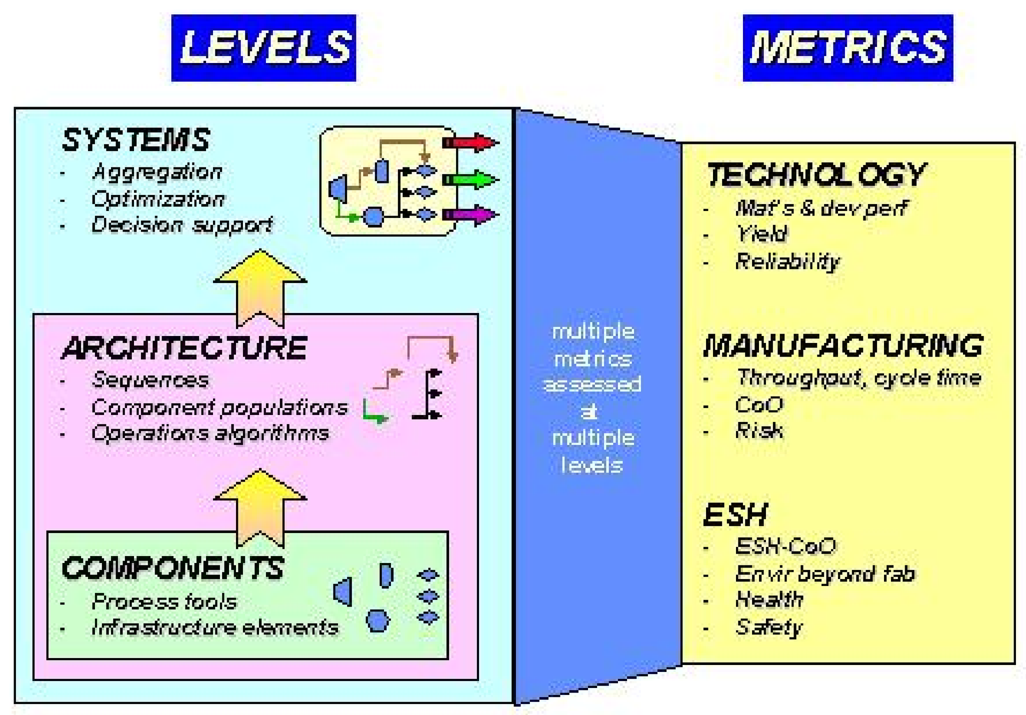
- Create models to assess ESH metrics at multiple levels
- Compare ESH metrics for
  - Conventional processes, with and without ESH infrastructure enhancements
  - Alterative processes

Systems engineering approach to achieve ESH benefits within the larger context of product performance and manufacturing metrics

- Develop models which reveal metrics for performance & manufacturing as well as ESH
- Co-optimize where possible; understand and prioritize tradeoffs elsewhere

Systemic implementation of DFE across the Center's research portfolio

Project Scope



Dynamic Simulation at the Unit Process Level

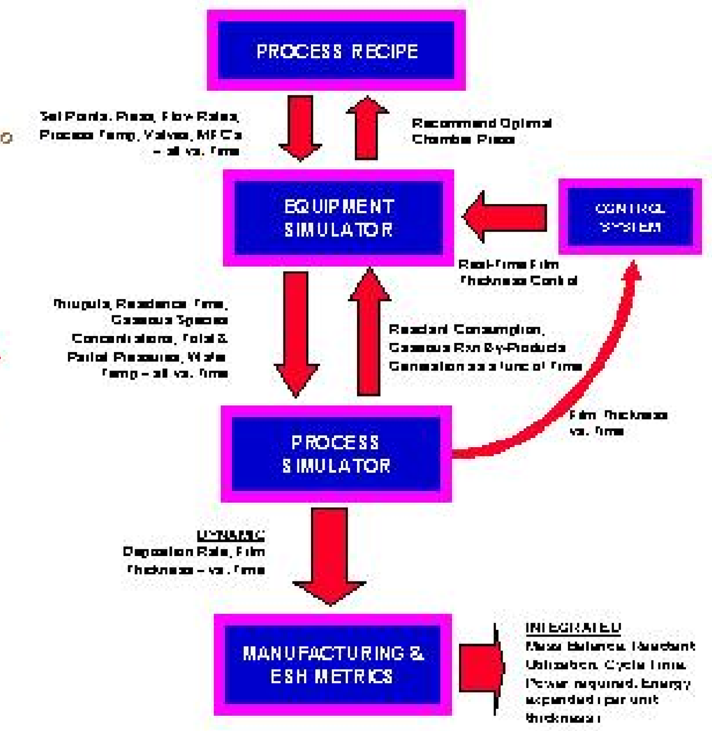
Unit Process: Simulation tools to generate manufacturing & ESH metrics

- *Static & Dynamic models & simulators to represent the time-dependent behavior of process & equipment*
- *Time-integrated behavior = manufacturing & ESH metrics*

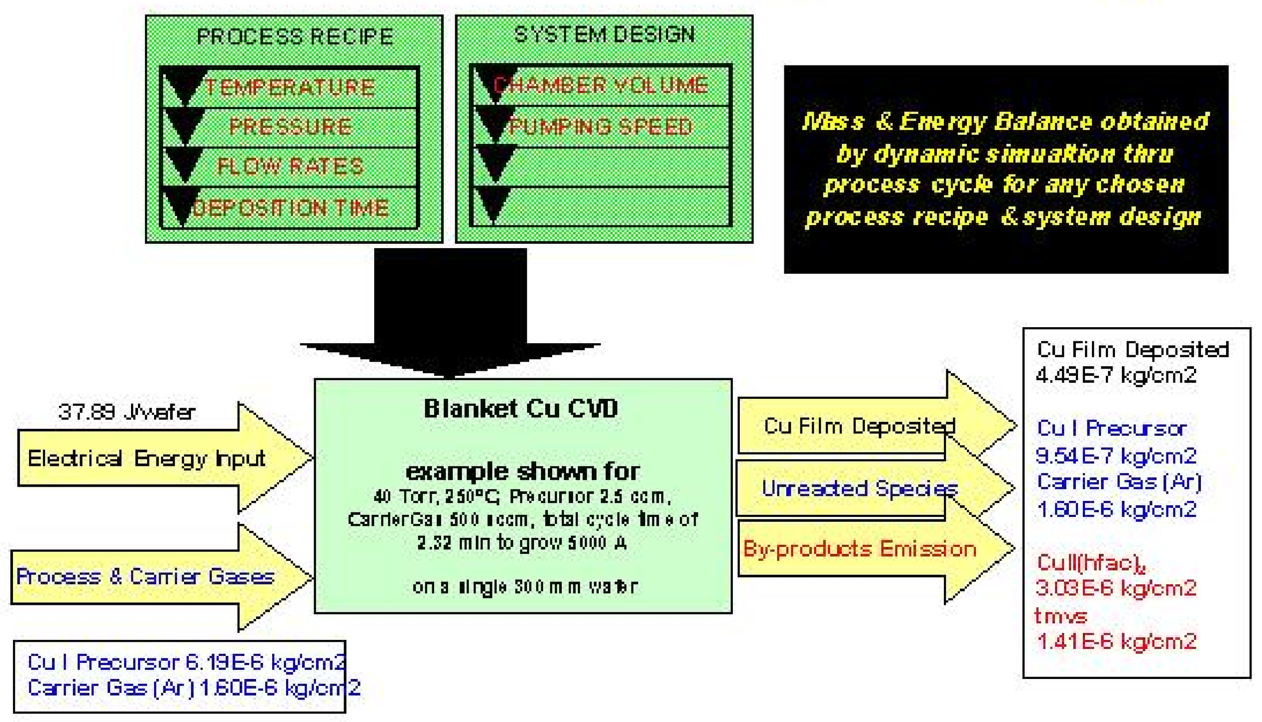
Unit process results to feed into operational levels (→ cluster tool → subfactory, etc.)

- *e.g.) tungsten plug factory model done within UMd research group*

See Demo



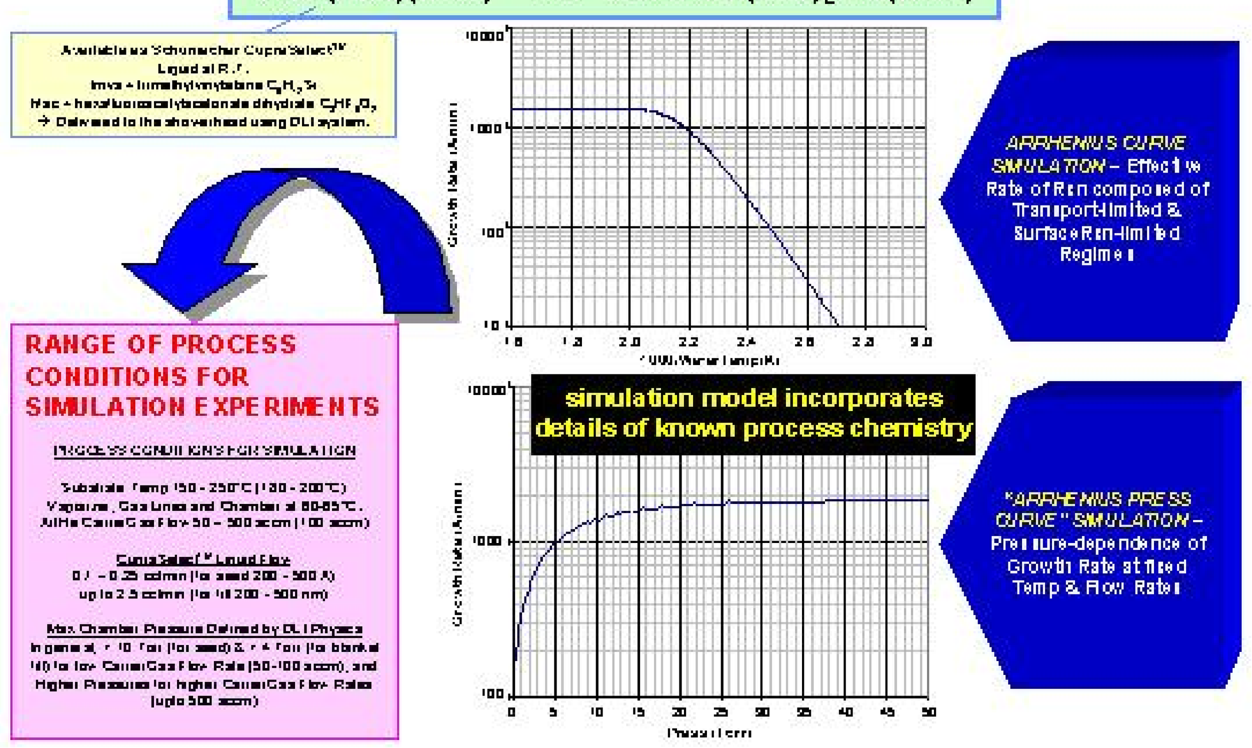
Mass & Energy Balance through Process Cycle



Blanket Cu CVD Process

$$2\ Cu^{I}(hfac)(tmvs) \rightarrow Cu^{0} + Cu^{II}(hfac)_2 + 2(tmvs)$$

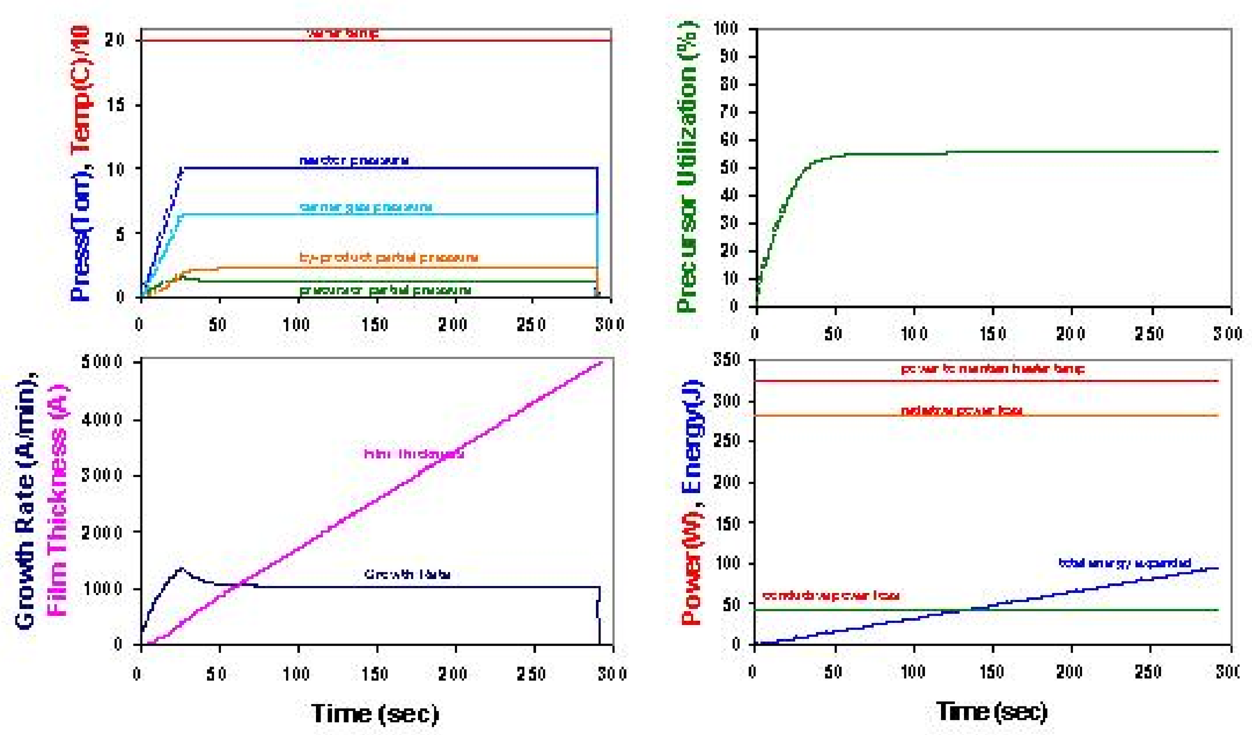
RANGE OF PROCESS CONDITIONS FOR SIMULATION EXPERIMENTS



ARRHENIUS CURVE SIMULATION – Effective Rate of Rxn composed of Transport-limited & Surface Rxn-limited Regimes

"ARRHENIUS PRESS CURVE" SIMULATION – Pressure-dependence of Growth Rate at fixed Temp & Flow Rates

Dynamics of Process / Equipment / Metrics

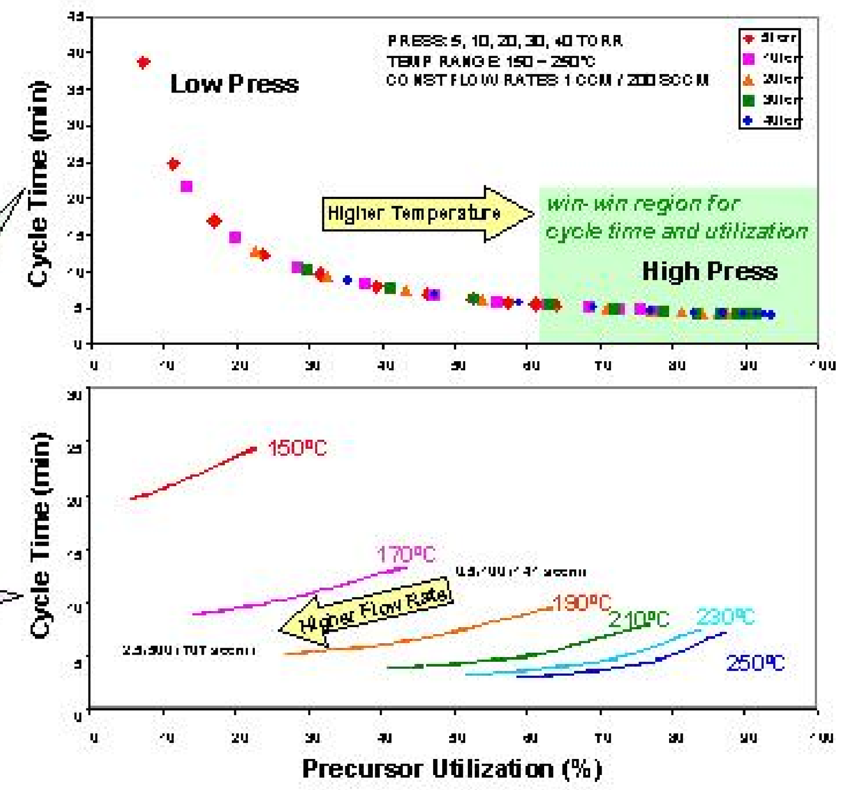


Cu CVD Co-Optimization for Manufacturing & ESH

CYCLE TIME - Manufacturing & **REACTANT UTILIZATION** - ESH & Manuf

High Press, High Temp → Win-Win Situation for Cycle Time & Utilization

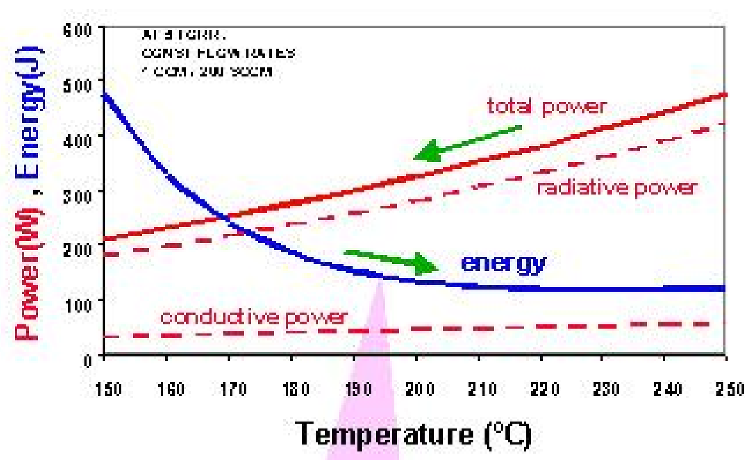
In the case of Flow Rate: Trade-off between Cycle Time & Utilization exists



Cu CVD Energy Optimization

Simulation

- *Power required to maintain wafer temp*
- *Energy expended per 500nm Cu deposited at that temp*



Higher temp requires more heating power

- Radiation ($\sim T^4$) and conduction ($\sim\Delta T$) are both important heat transfer channels in the process temperature regime for Cu CVD
- Maintaining higher temperature incurs higher power input
- ➔expect to prefer lower temperature to save energy

ENERGY OPTIMIZATION

- *Growth Rate rises exponentially with temp (Arrhenius behavior, thermally activated process)*
- *➔shorter cycle time*
- *➔reduced energy cost*

Temp dependence of energy usage is dominated by cycle time effect, not by power needs for maintaining wafer temp

Conclusions

Methodology

Typically, ESH impact metrics are evaluated empirically once processes are known.

The dynamic simulation tools developed and used here enable co-optimization of ESH and manufacturing metrics as a function of process recipe variables and equipment design choices.

Manufacturing Metrics

Simulation models show benefits in both process cycle time and materials consumption at higher temperature and pressure, along with trade-offs between cycle time and materials consumption as a function of flow rate.

ESH Metrics

Materials consumption may be increased as much as ≥2X at higher temperature, accompanied by a modest benefit in manufacturing throughput (materials performance and yield consequences TBD).

Energy consumption may also be reduced by 2X using higher temperature (210 vs. 160°C). Higher temperature reduces energy use because thermal activation of process increases deposition rates with temperature faster than heating power in this process parameter domain.

Significance

Modeling approach provides generic platform for optimization and trade-off analysis for multiple metrics