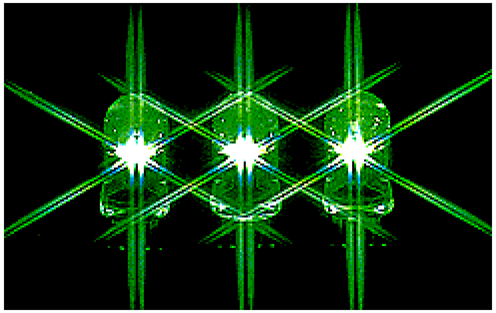
# Combinatorial Optimization of Ohmic Contacts to GaN Semiconductor

A.V. Davydov[1], W.J. Boettinger[1], L.A. Bendersky[1], D. Josell[1], A.J. Shapiro[1], U.R. Kattner[1],
P.K. Schenck[2], J.E. Blendell[2], R.S. Gates[2], M.D. Vaudin[2],
A. Motayed[3], K.-S. Chang[4], I. Takeuchi[4], Q. Z. Xue[5]
[1] Metallurgy Division / [2]Ceramic Division, NIST, Gaithersburg, MD
[3] MSRCE, Howard University, Washington, DC
[4] Dept. of Mat. Sci. & Eng., Univ. of Maryland, College Park, MD
[5] Intematix Corp., Moraga, CA

- Why GaN?
- Metallization Issues to GaN Devices
- Approach: Combi- Integrated with Phase Diagram/Kinetic Knowledge
- Au/Ni contacts
- Al/Ti-based contacts
- Summary

**NCMC-5 Meeting, April 26, 2004**

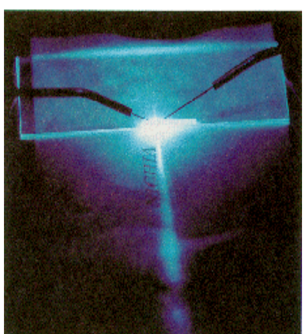
# Gallium Nitride Optoelectronic Applications



GaN-based **LED**
(520 nm)

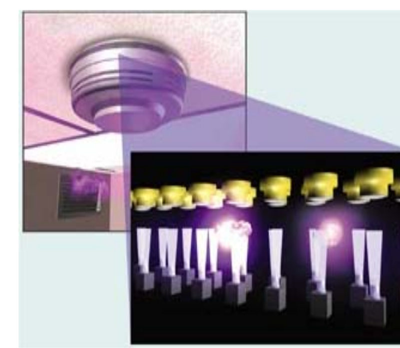

Traffic Lights


Full-color LED Displays



GaN **Laser**
(450 nm)

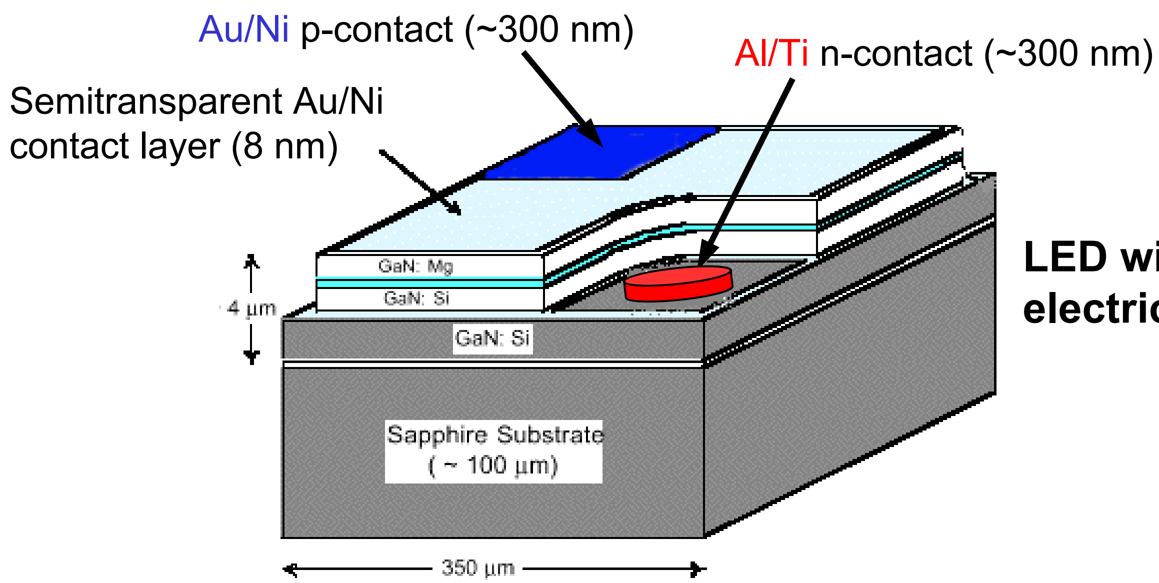

Data Storage



UV Bio-sensors

”The market for GaN-bases devices is $1.5B and will grow to $4.5B by 2007”
[Strategies Unlimited Report, 2003 ]

# Metallization Issues in Nitride Optoelectronic Devices

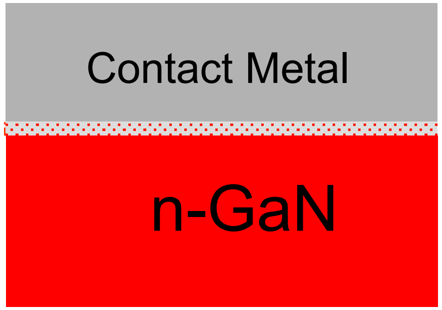



**LED with the Ni/Au and Ti/Al electrical contacts**

- **Metal contact problems:**
  - high resistance (especially for p-GaN)
  - poor morphology
  - low light transmittance (essential for p-type contacts!)
  - low thermal stability: degradation above ~ 400 - 500°C
  - **mechanisms for contact formation not currently understood**
  - **metallization scheme not optimized**

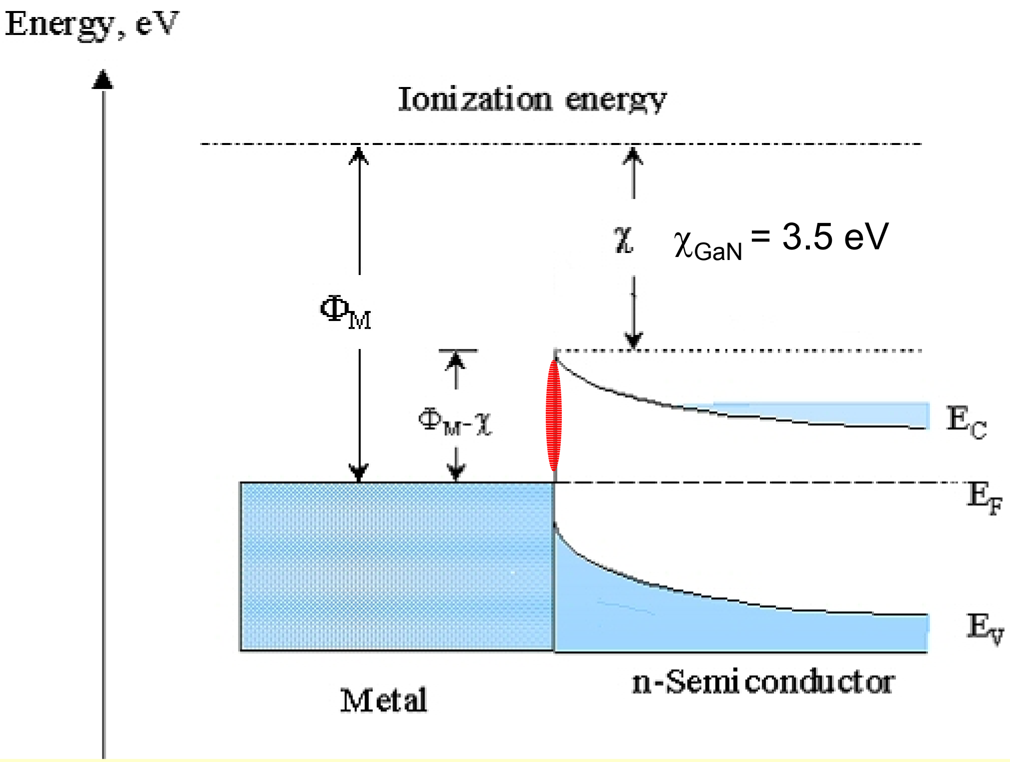
**Industry Goal:**
**low-resistive (<$10^{-5}$ $\Omega cm^2$), transparent (p-GaN), thermally stable (up to 600°C) contacts**

# Metal/Semiconductor Interface: Key to Ohmic Behavior




- Metal Deposition
- Annealing !

Ohmic contact: $\Phi_M \leq \chi_{GaN}$




**Goal:**

- Develop metallization approach and information to realize optimum Ohmic contacts

**Approach:**

- Quantify "structure-property" relationship (SPR): contact characteristics ↔ microstructure
- Design optimum electrical contact using SPR knowledge

**Tools:**

- Employ Combi- & Phase Diagram Approach as a framework for SPR

# Engineering Steps for Ohmic Contact

**Step 1:** Contact design: choose metal scheme and processing schedule

**Step 2:** Contact deposition/processing

**Step 3:** Contact characterization

**Step 4:** "Structure-Property" relationship: correlating electrical properties with microstructure

## Approach:

**Step 1:**

- contact properties defined by multiple variables

↓

- use combinatorial approach
- use phase diagram knowledge

} for experiment design

**Steps 2:**

- use combinatorial deposition and processing

**Steps 3:**

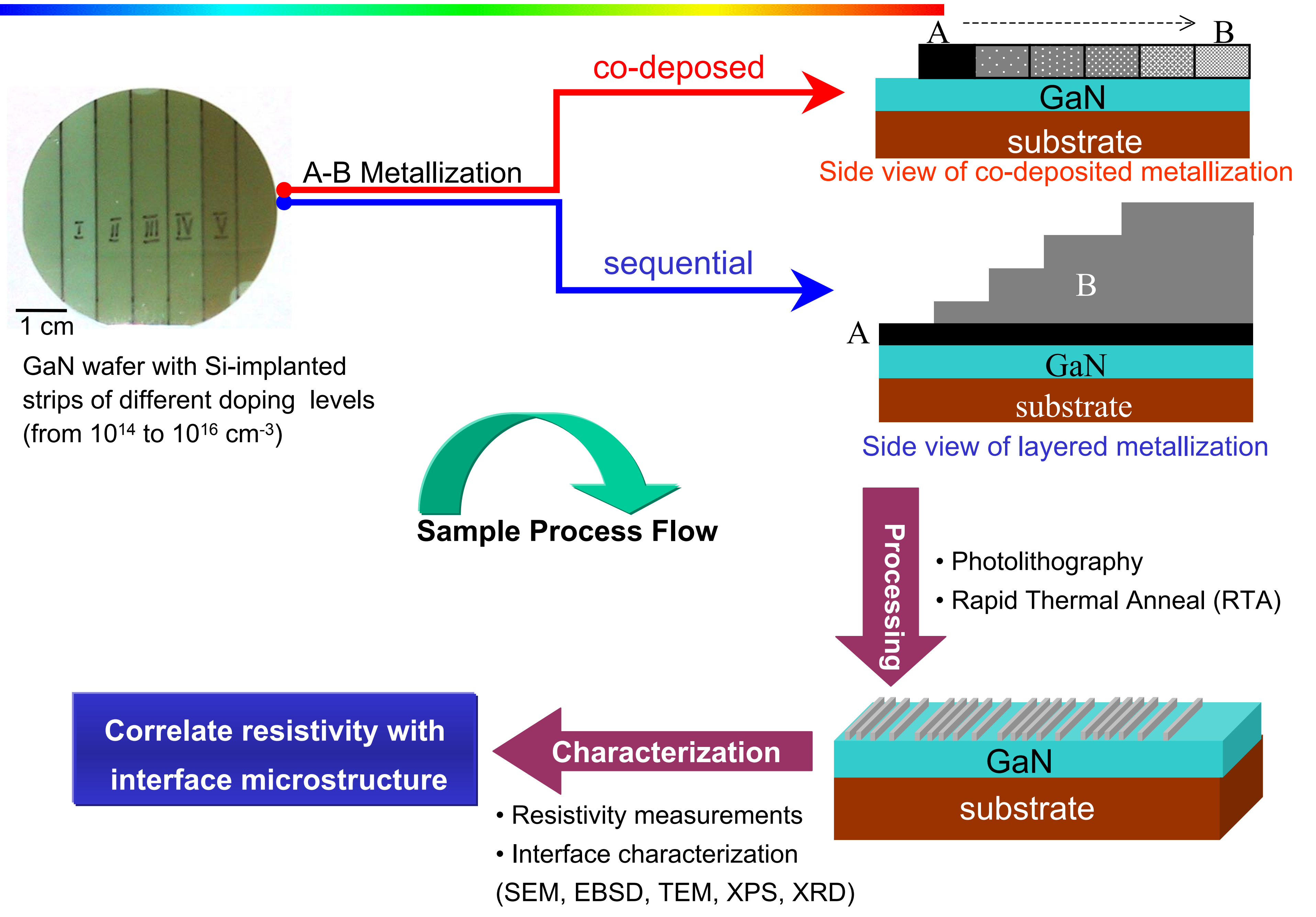
- use high-throughput characterization

**Step 4:**

- use phase diagram and kinetic knowledge to interpret microstructure

Integrated Combi- and Phase Diagram/Kinetic Approach is proposed

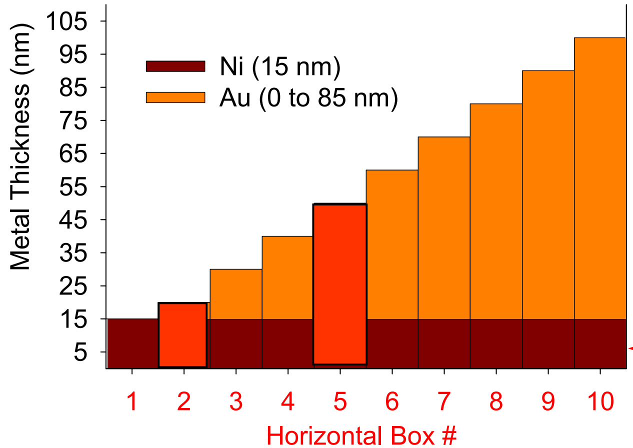
# Metal/GaN Combinatorial Sample Flow



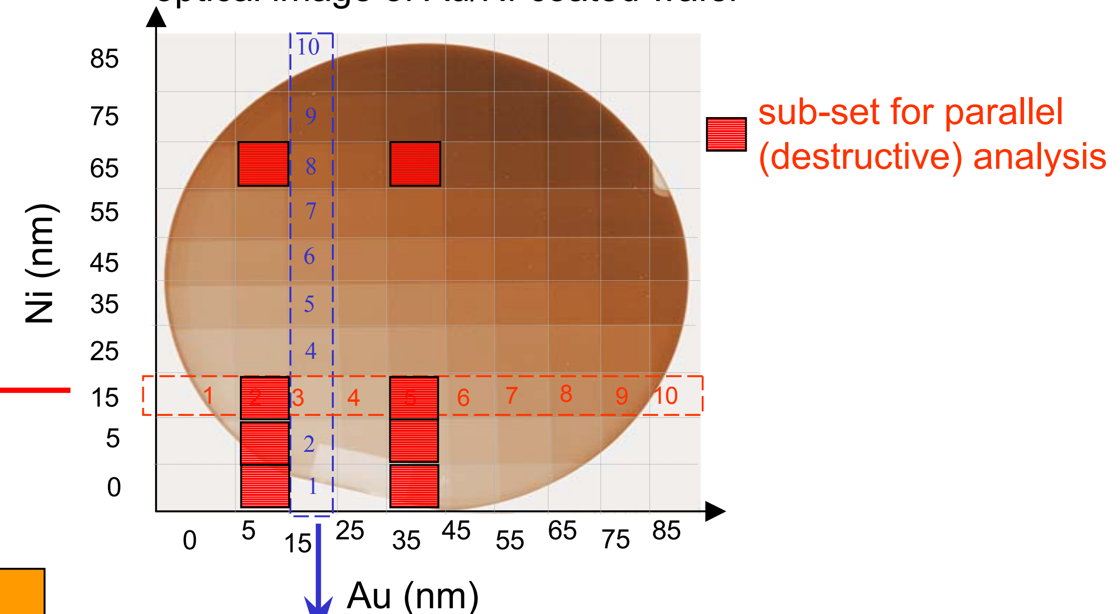
# Au/Ni Contact Library on GaN

**Goal:** Identify library elements that are: a) transparent, b) good crystalline quality

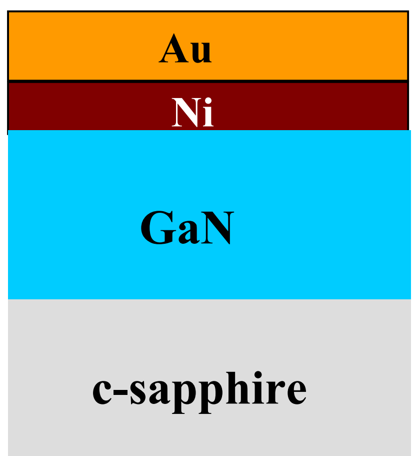
# Au/Ni Contact Library on GaN



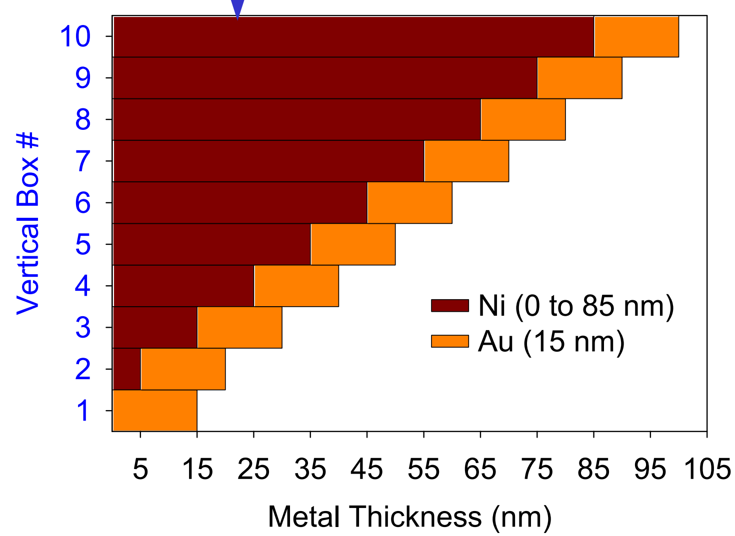

optical image of Au/Ni-coated wafer



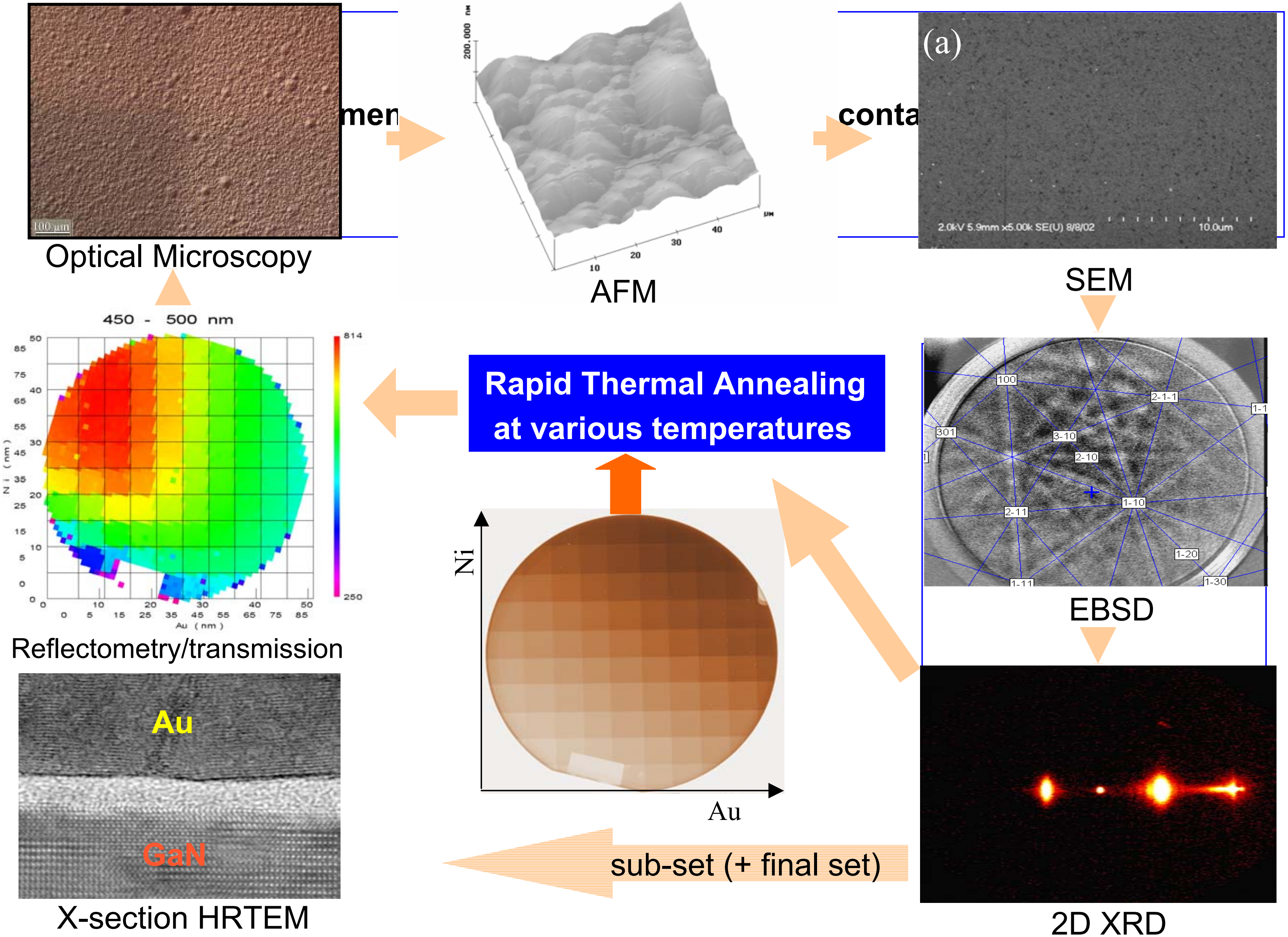

e-beam evaporated metallization with variation of Ni/Au layer thicknesses




X-section of an element

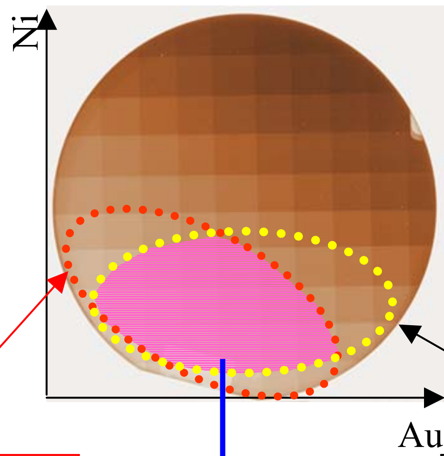


# Au/Ni Combinatorial Library Screening



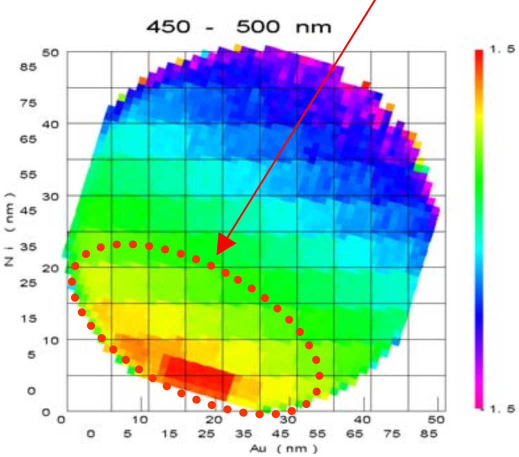

Focus: correlate optical & morphological quality of contacts with microstructure

# Optimum Performance Region of Au/Ni Metallized Wafer

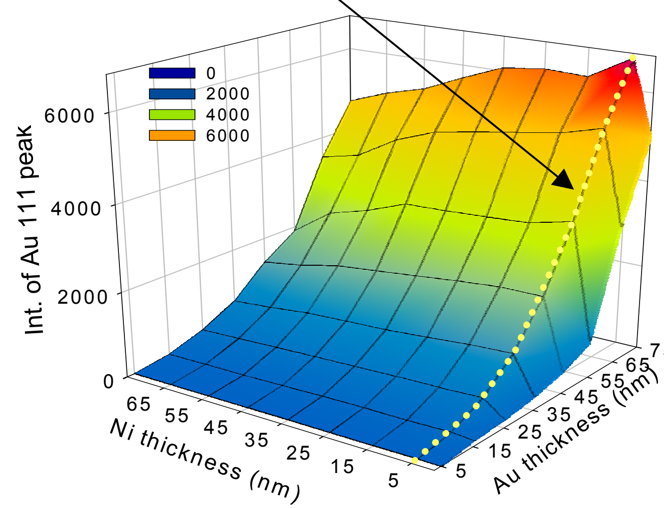



Area of Maximum Transparency

Area of Best Crystallinity




Transmission Measurements




XRD mapping of Au 111 peak

Optimum Au/Ni composition with transparent, good crystalline quality as-deposited metal contacts

Applied Surface Science, v. 223(1-3), p.24 and p.200 (2004)

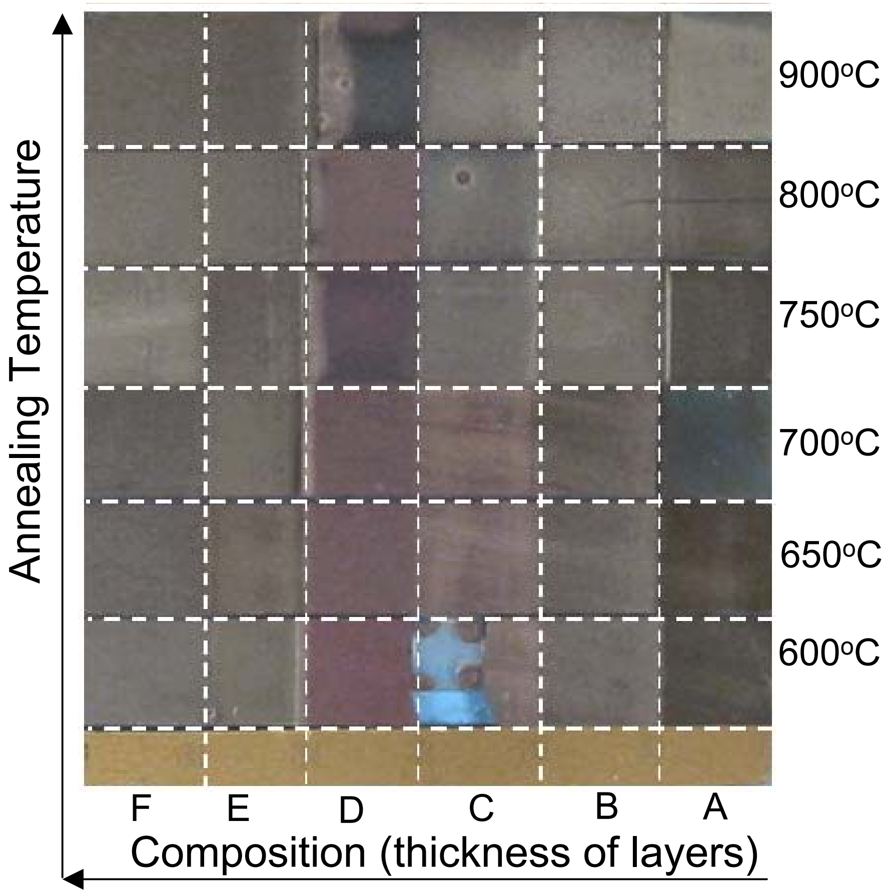
# Ti/Al/Ti/Au Contact Library on n-GaN

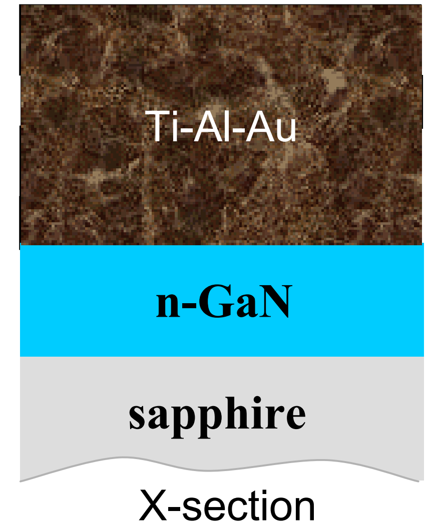
Goal: optimize contact resistance and morphology as a function of:

- Ti/Al/Ti/Au ratio
- Annealing Temperature

# Ti/Al/Ti/Au Contact Library on n-GaN

Ti/Al/Ti/Au is Industry-standard Metallization

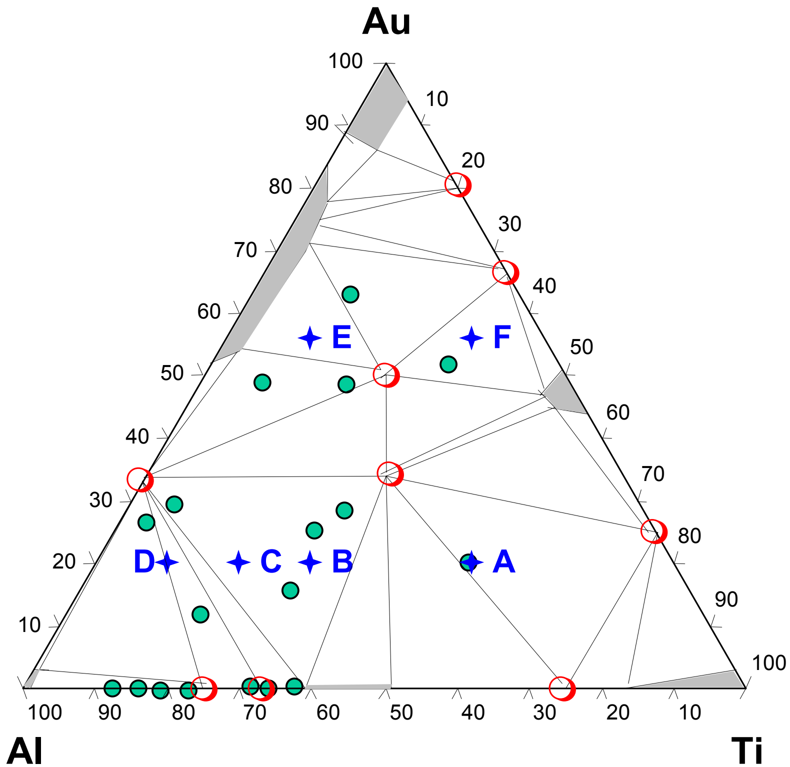



Measurements:
- electrical: contact resistivity; Hall
- structural: FESEM, WLI, XRD, TEM

Criteria: low resistivity ($\rho < 3E\text{-}5\ \Omega\ cm^2$) + smooth surface morphology (Rms < 60 nm)

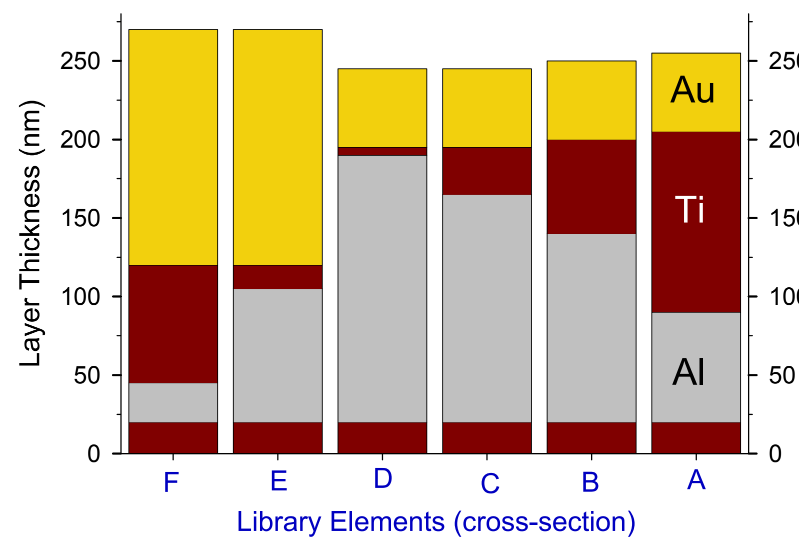
# Library Design using Ti-Al-Au Phase Diagram




Schematic Ti-Al-Au Phase Diagram (T~800 $^{o}$C)

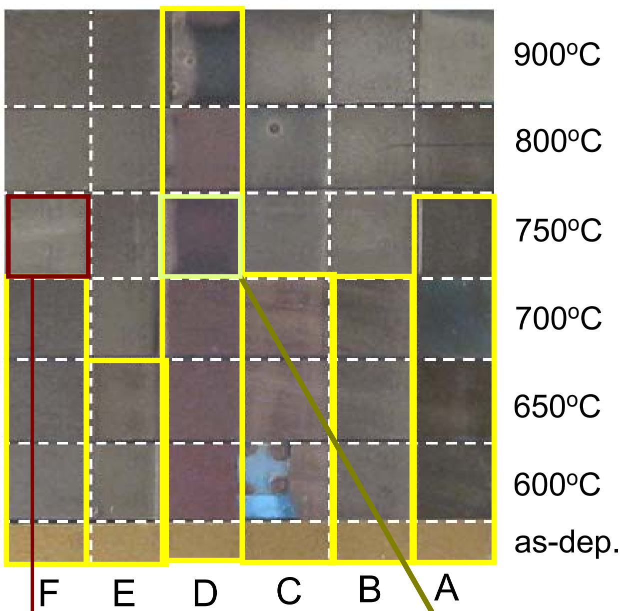

● Ti:Al:Au contact compositions from literature

+ Library compositions

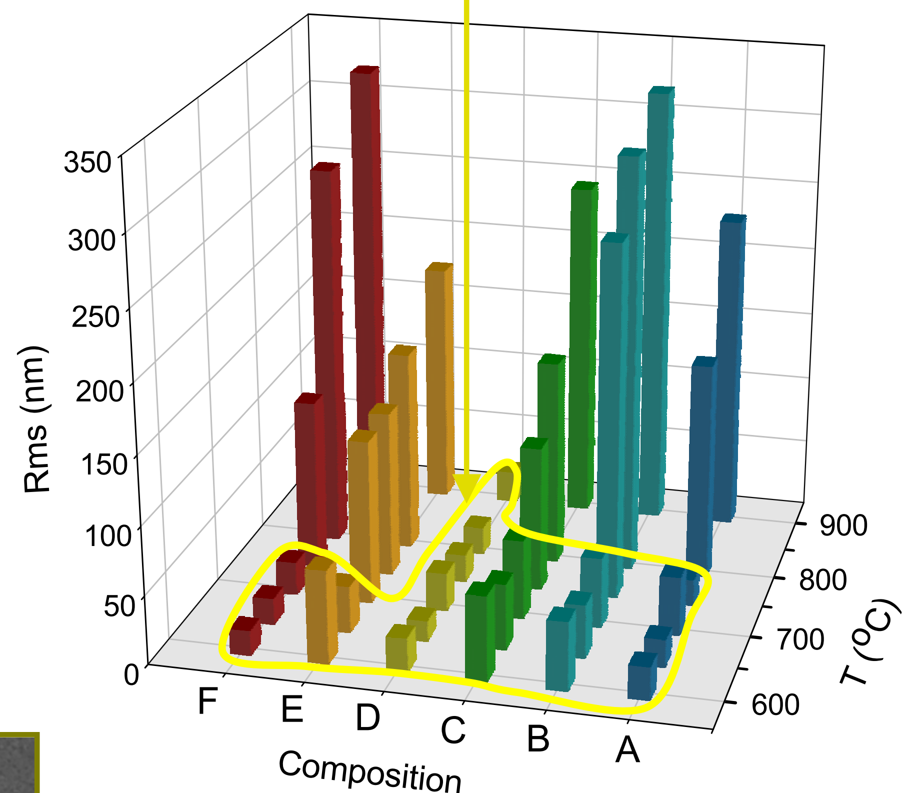


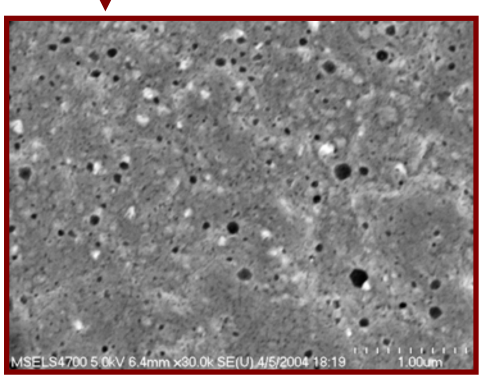
# Contact Morphology

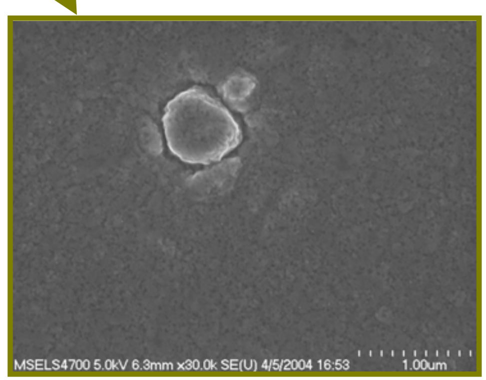
Roughness assessed with: WLI, AFM, FESEM




Roughness criteria: Rms < 60 nm



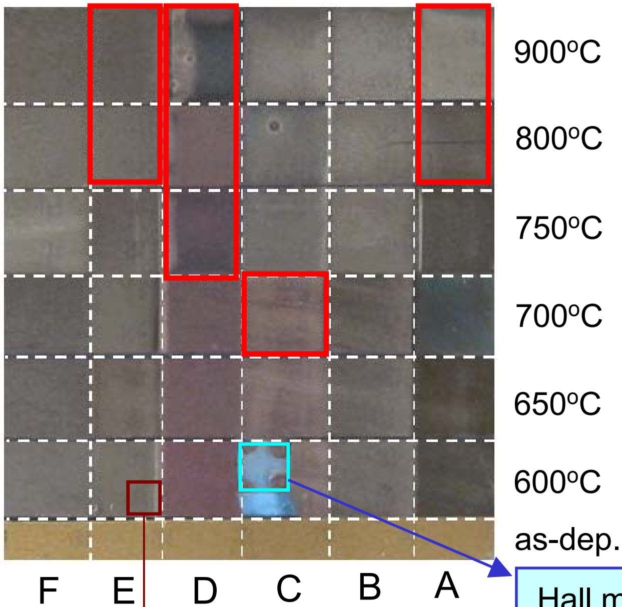

FESEM: Plane View x30K

Strip "D" has smoothest surface:

Rms = 15-28 nm

(possibly due to liquid phase formed at $T_{RTA}$)

# Contact Resistivity

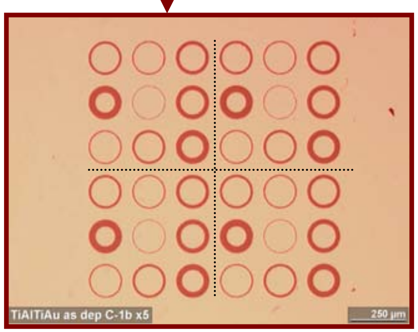



**Hall measurements:**

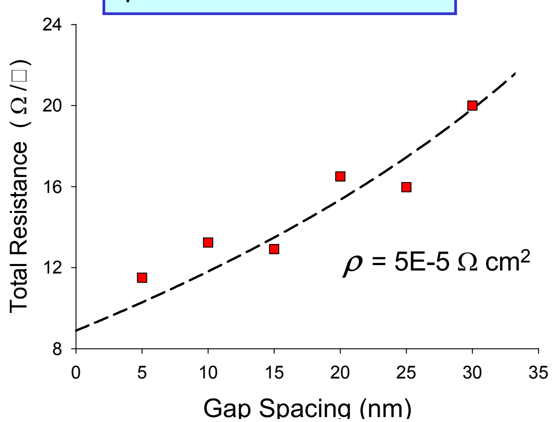
$n$ = 1.7-2.7 E18 $cm^{-3}$

$R_{sh}$ = 16.2-18.1 Ω/□

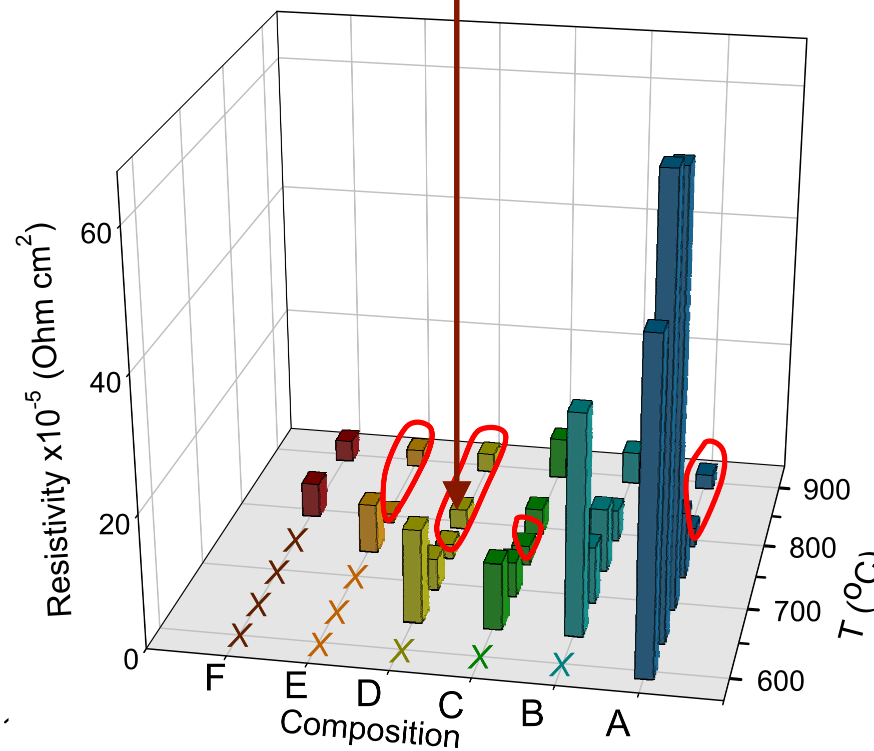
μ = 202-314 $cm^2V^{-1}s^{-1}$




Transfer Length Model (TLM)




Low resistivity criteria : $\rho$ < 3E-5 Ω cm²




Sample "E-800ºC" has lowest contact resistivity

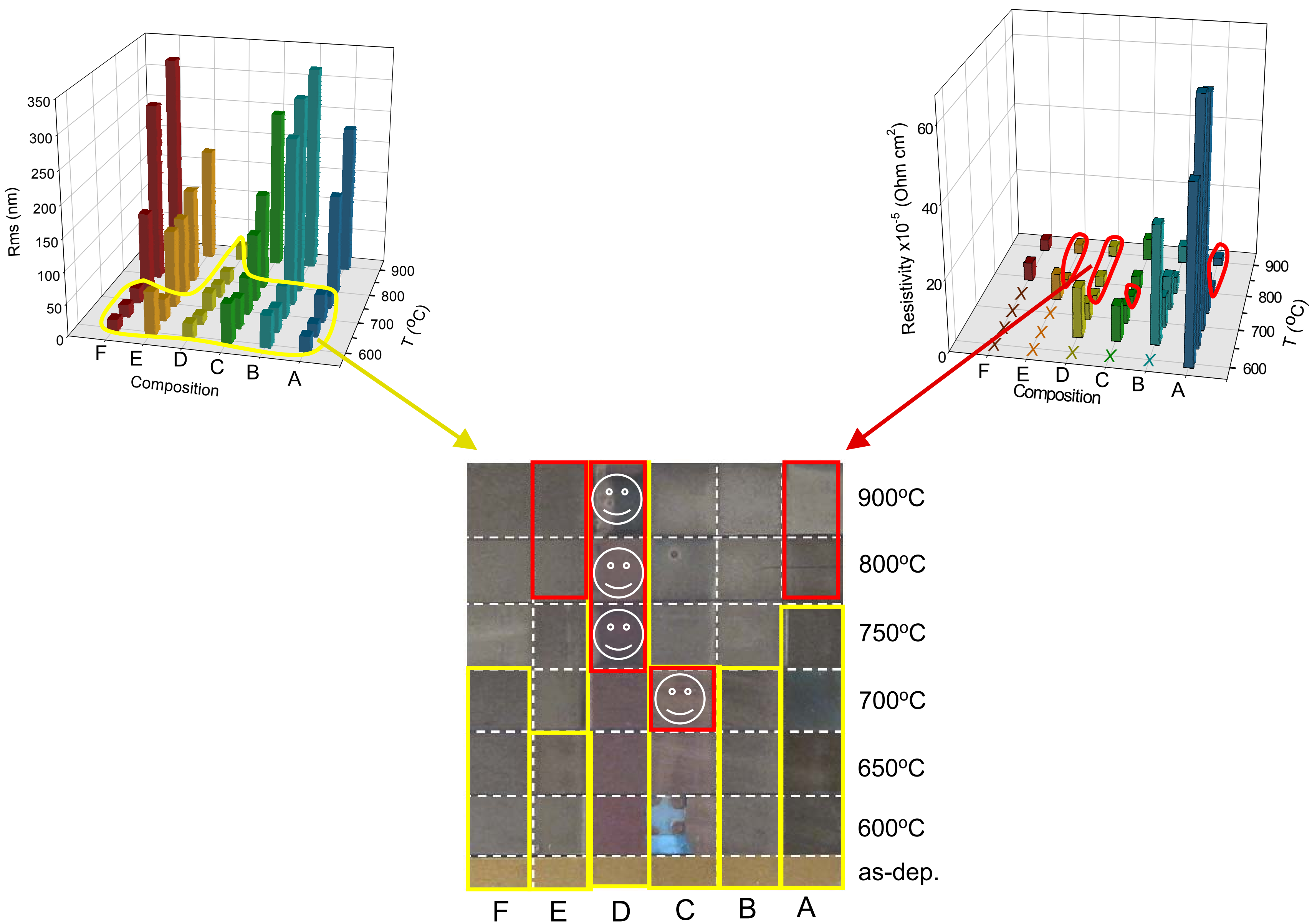
$\rho$ = 1.3E-5 Ω cm²

(Study interface: TEM, spreading resistance)

$$R_{total} = \frac{R_{sh}}{2\pi}\left[\frac{L_t}{R_0}\frac{I_0(R_0/L_t)}{I_1(R_0/L_t)} + \frac{L_t}{R_1}\frac{K_0(R_1/L_t)}{K_1(R_1/L_t)} + \ln\left(\frac{R_1}{R_0}\right)\right]$$

$$\rho = L_t^2 R_{sh}$$

# Optimum Morphology and Resistivity of Contact Library



# Summary: Approach and Long-term Goals

- Approach:

Develop integrated approach of combinatorial material science with thermodynamic & kinetic knowledge, in which phase diagram & diffusion databank offers a framework for high-throughput experimentation

- Future Plans:
  - Develop thermodynamic/diffusion databases for the Metal-Semiconductor systems (e.g., Metals: Au-Ni-Al-Ti; Semiconductors: GaN, ZnO)
  - Use this data to construct ***processing model*** to enable design of optimum metal contacts to industrially important semiconductors