Roll Printing of Nanomaterials for Integrated Electronics and Sensors

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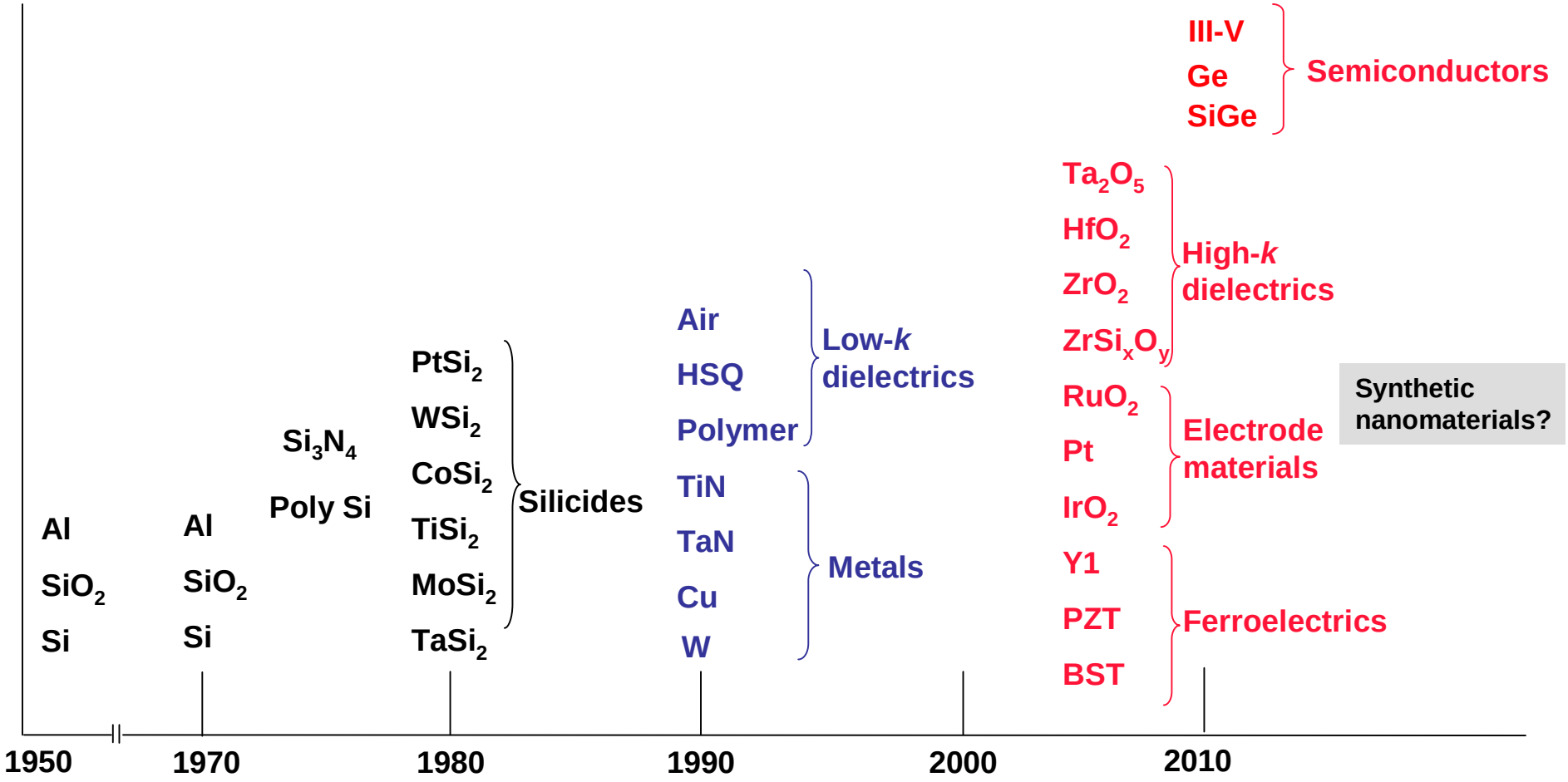
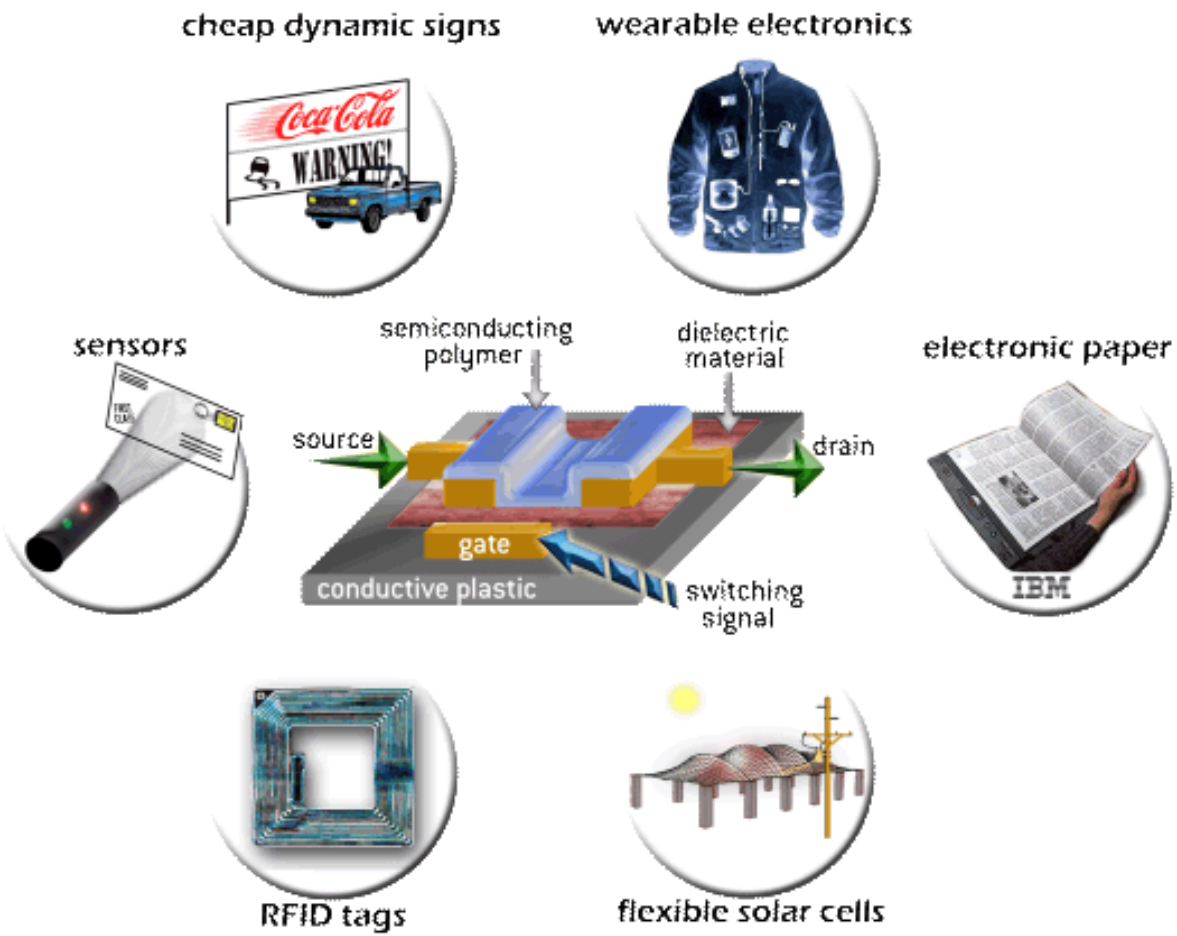
New Materials as the Key Differentiator



Moore's Law increasingly relies on material innovations

Macroelectronics: Printing Electronic Materials on Foreign Substrates



NIST

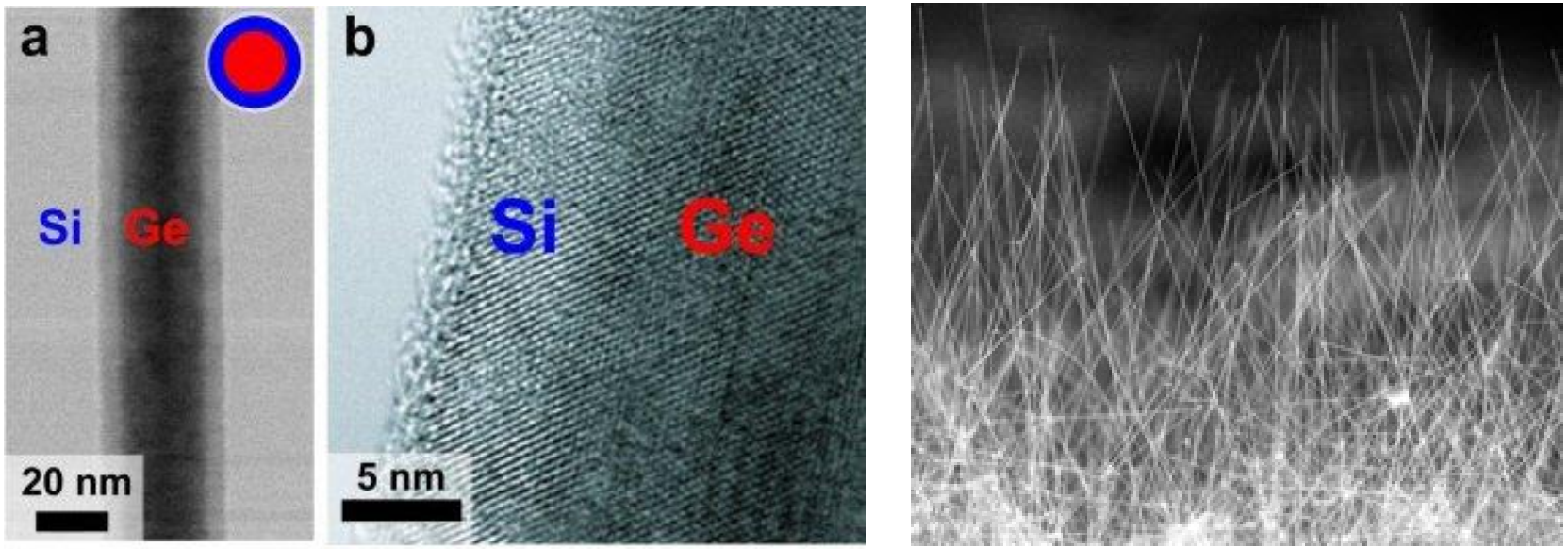
Problems with Organic Electronics

1. Lack of performance

2. Lack of stability

Therefore, there is a need for materials innovation to enable high performance, printable electronics

Why Nanowires?



1. Single crystalline, 1D with atomically defined surfaces and composition

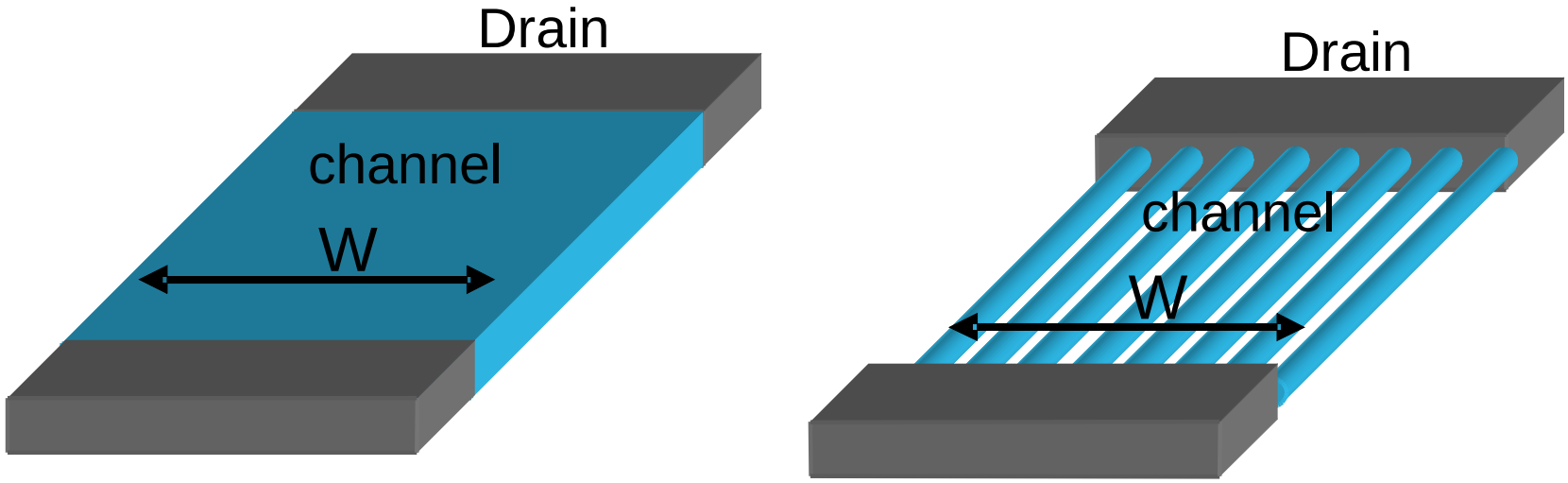
2. Wide range of materials

Si, Ge, Si/Ge, InAs, GaAs, CdSe, ZnO, Pt, Au, ….

3. Ambient temperature processing:

Heterogeneous integration, 3-D stacking, plastic electronics,…

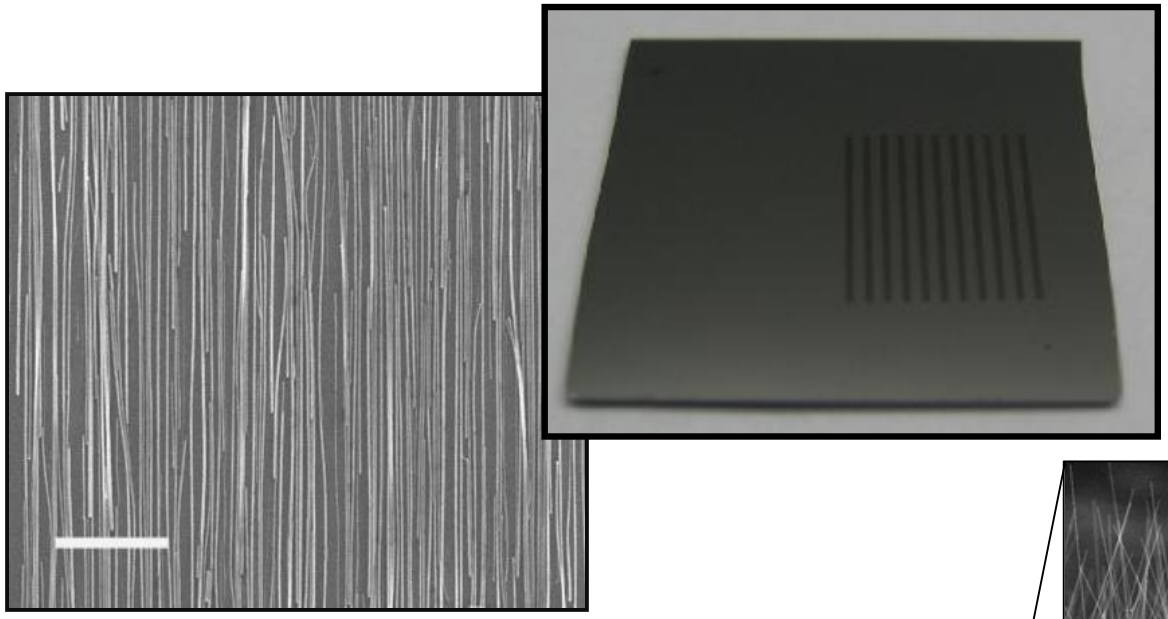
Assembly of Parallel Array NWs



Nanowire Assembly Requirements:

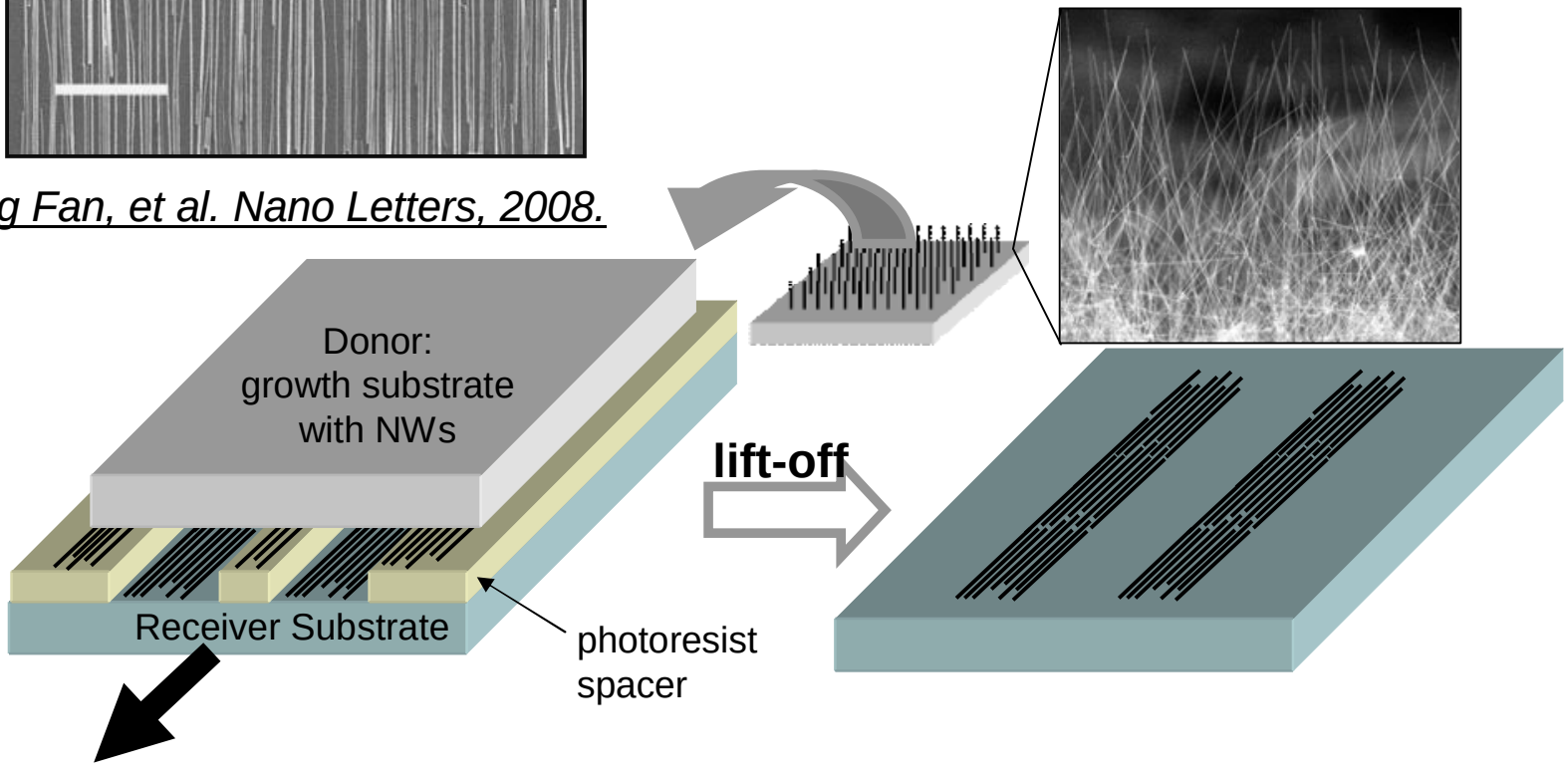
- -Well Aligned
- -Tunable Density
- -Clean
- -Scalable

Contact Printing of Nanowires

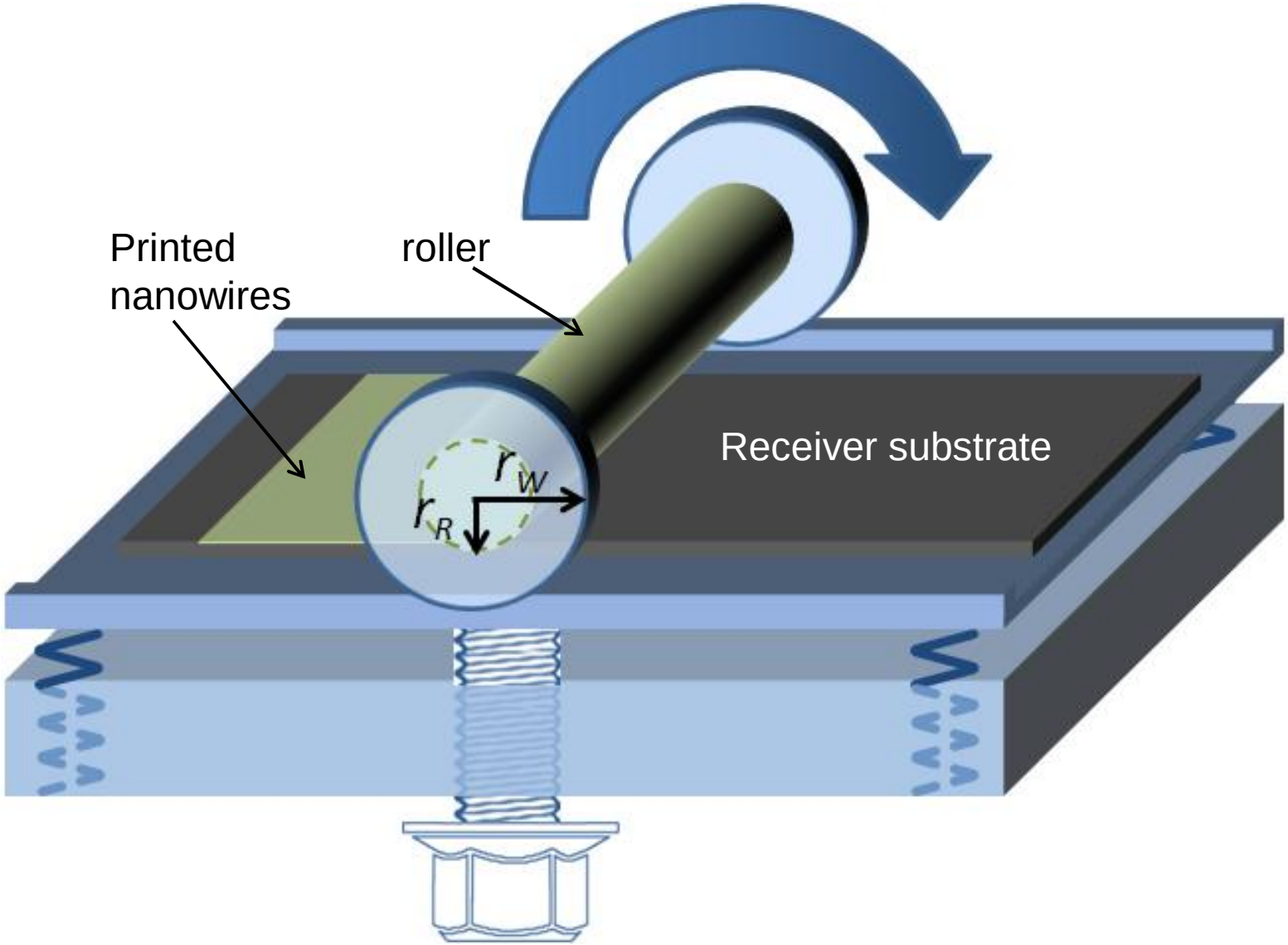


- **Well Aligned**
- **High Density**
- **Quick**
- **Clean**
- **Uniform**
- **Cheap**
- **Any substrate**

Zhiyong Fan, et al. Nano Letters, 2008.

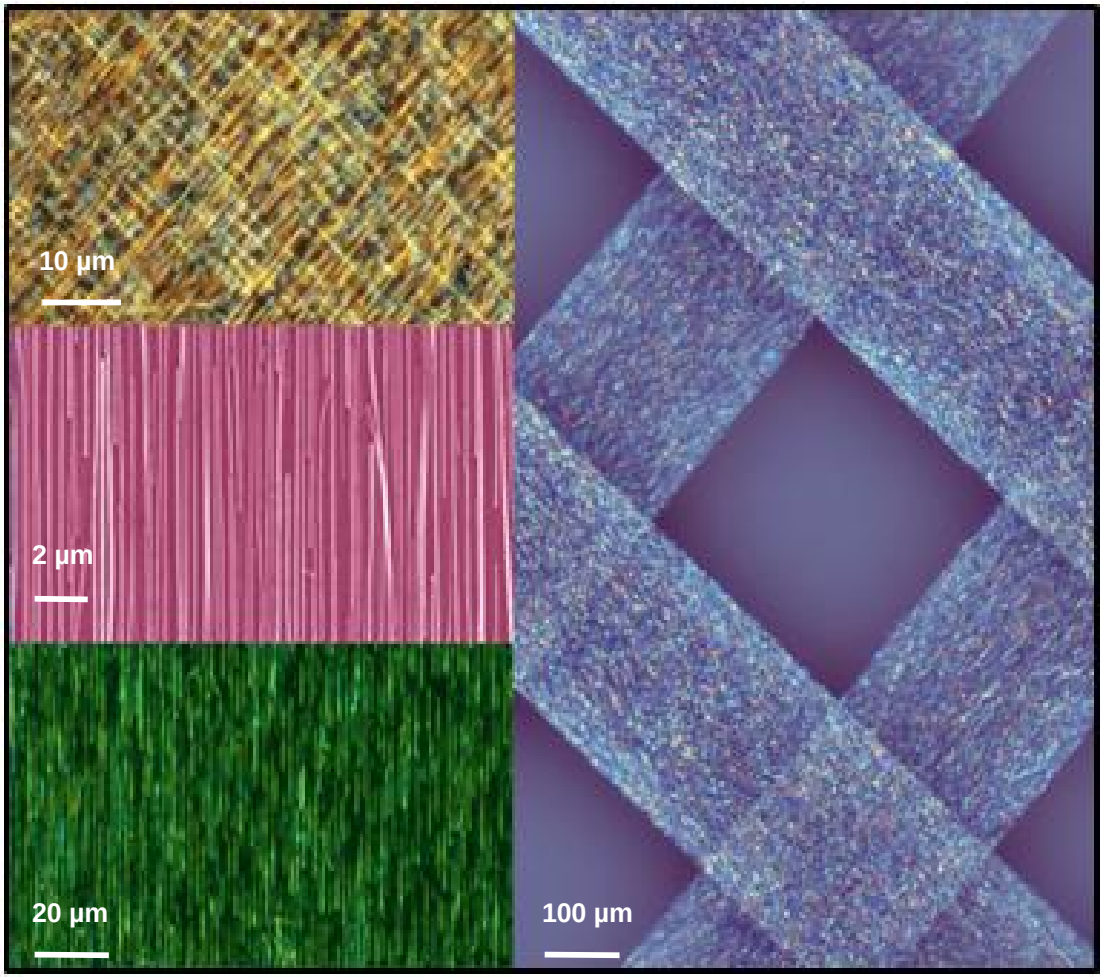


Roller printing of NWs

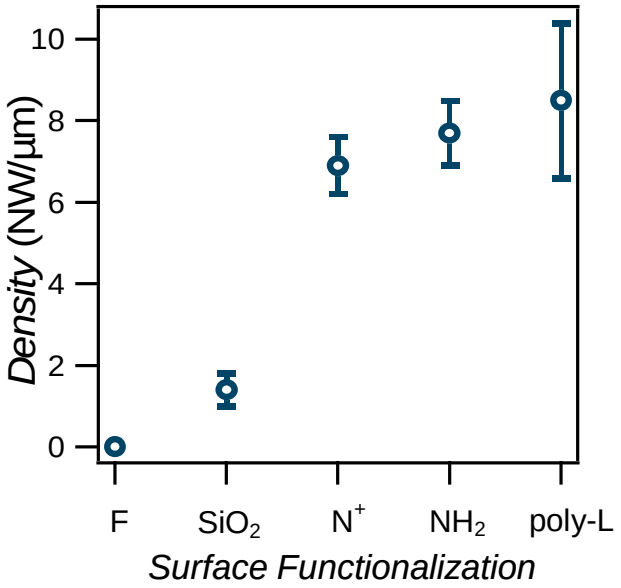


R. Yerushalmi, et al. Applied Physics Letters, 2007.

Assembly of Nanowire Superstructures



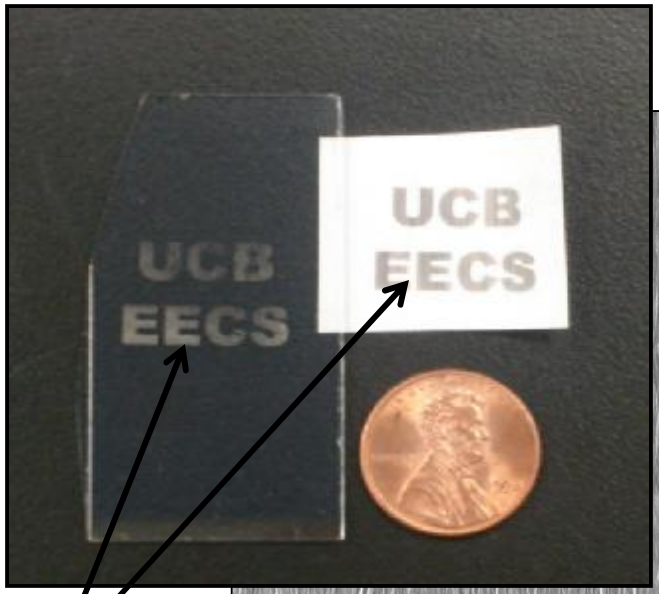
Nanowire superstructures can be readily assembled on substrate by contact printing

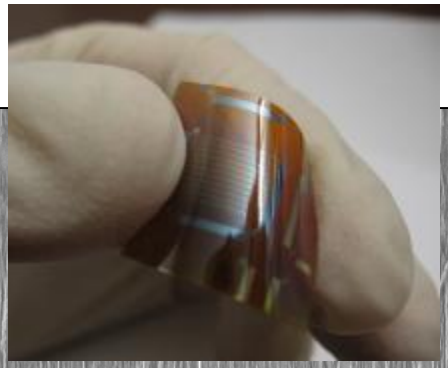


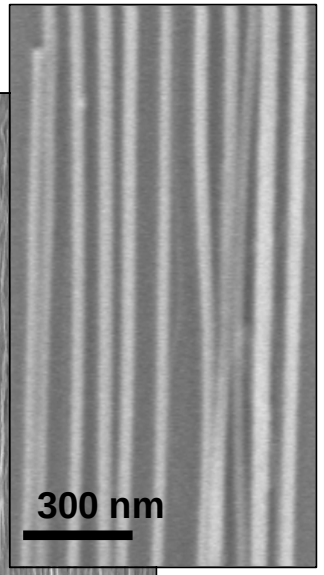
- The assembled nanowire length can be readily tuned by the growth nanowire length.

- The density of nanowires can be well tuned by surface modification in order to meet the specific application needs

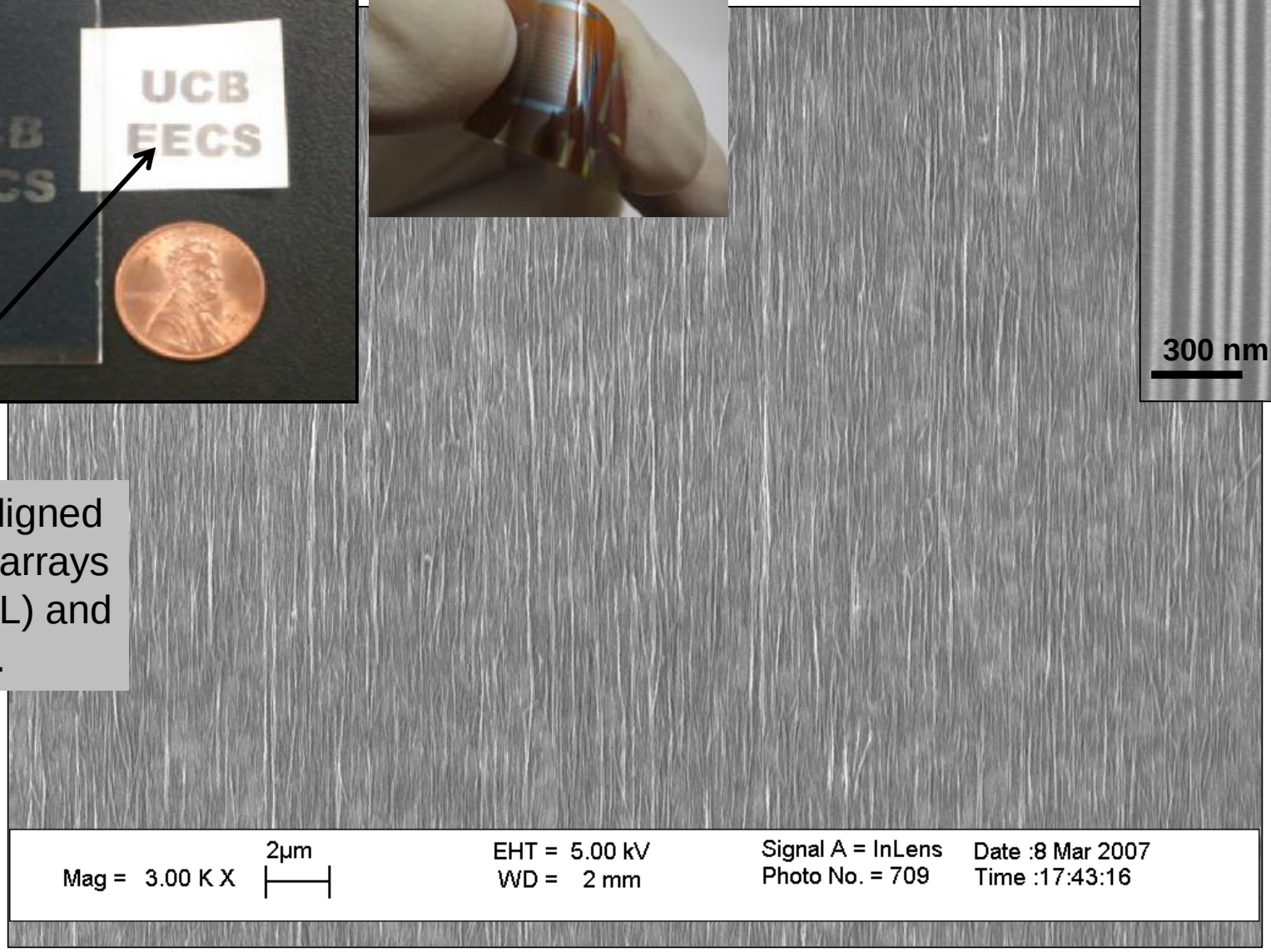
High Density NW Array



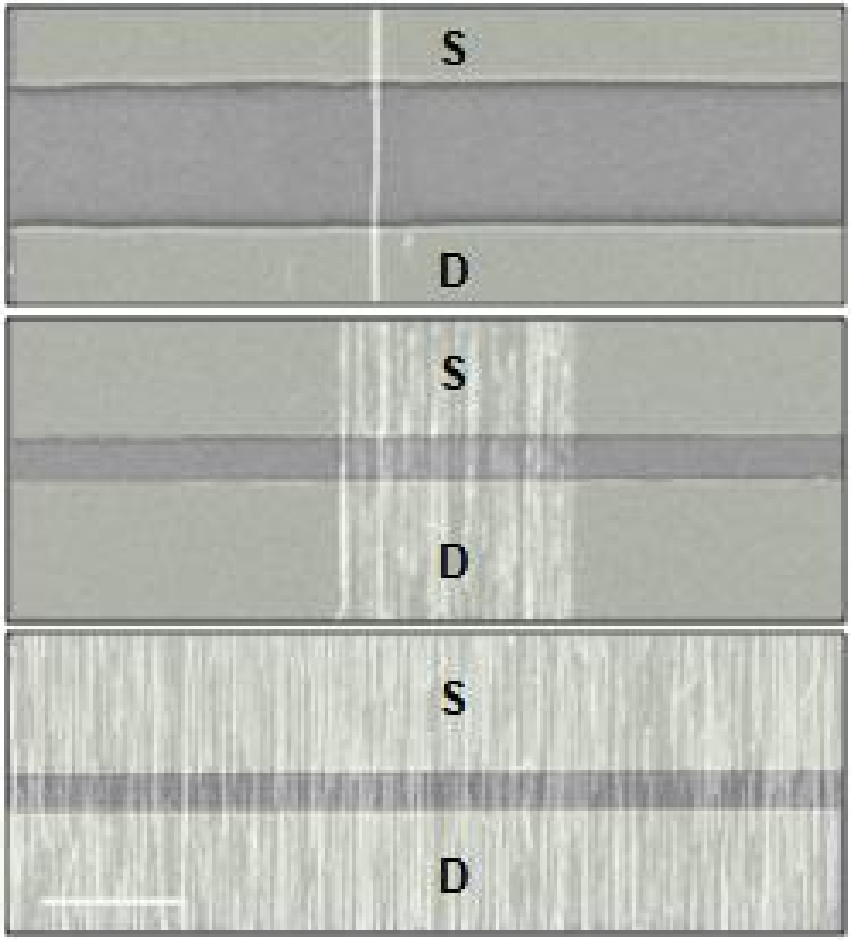


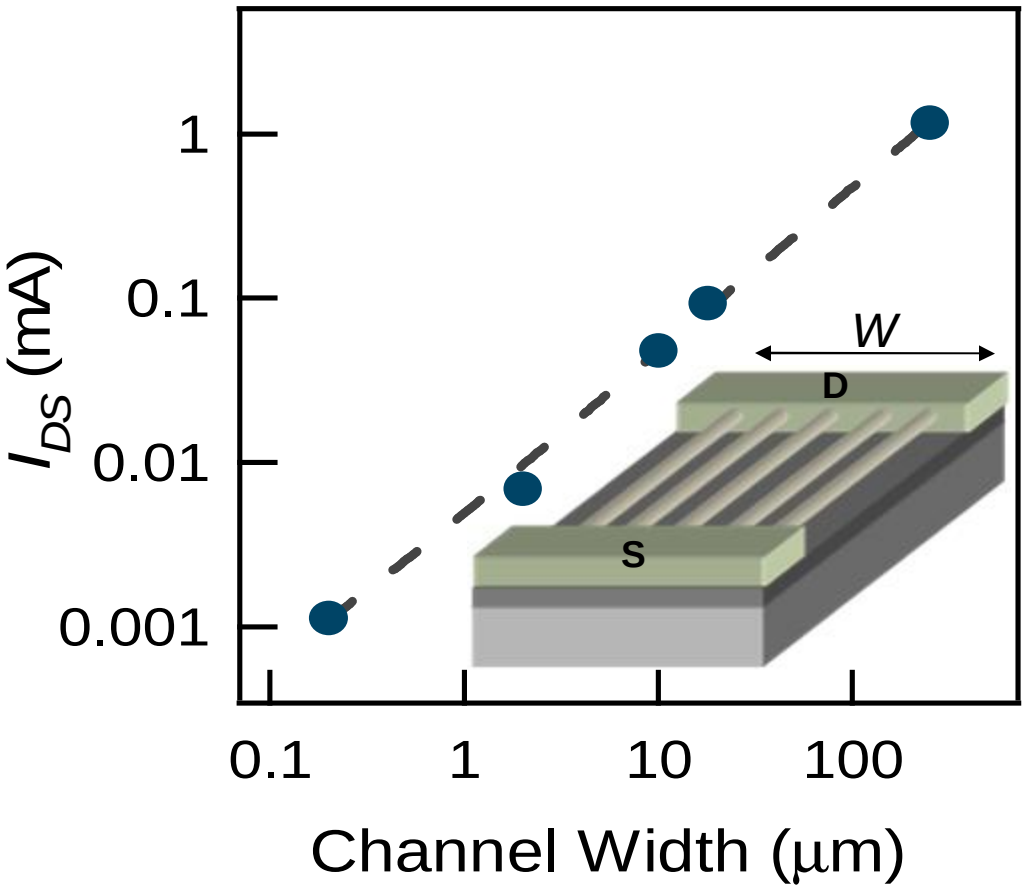


Printed, aligned nanowire arrays on glass (L) and paper (R).



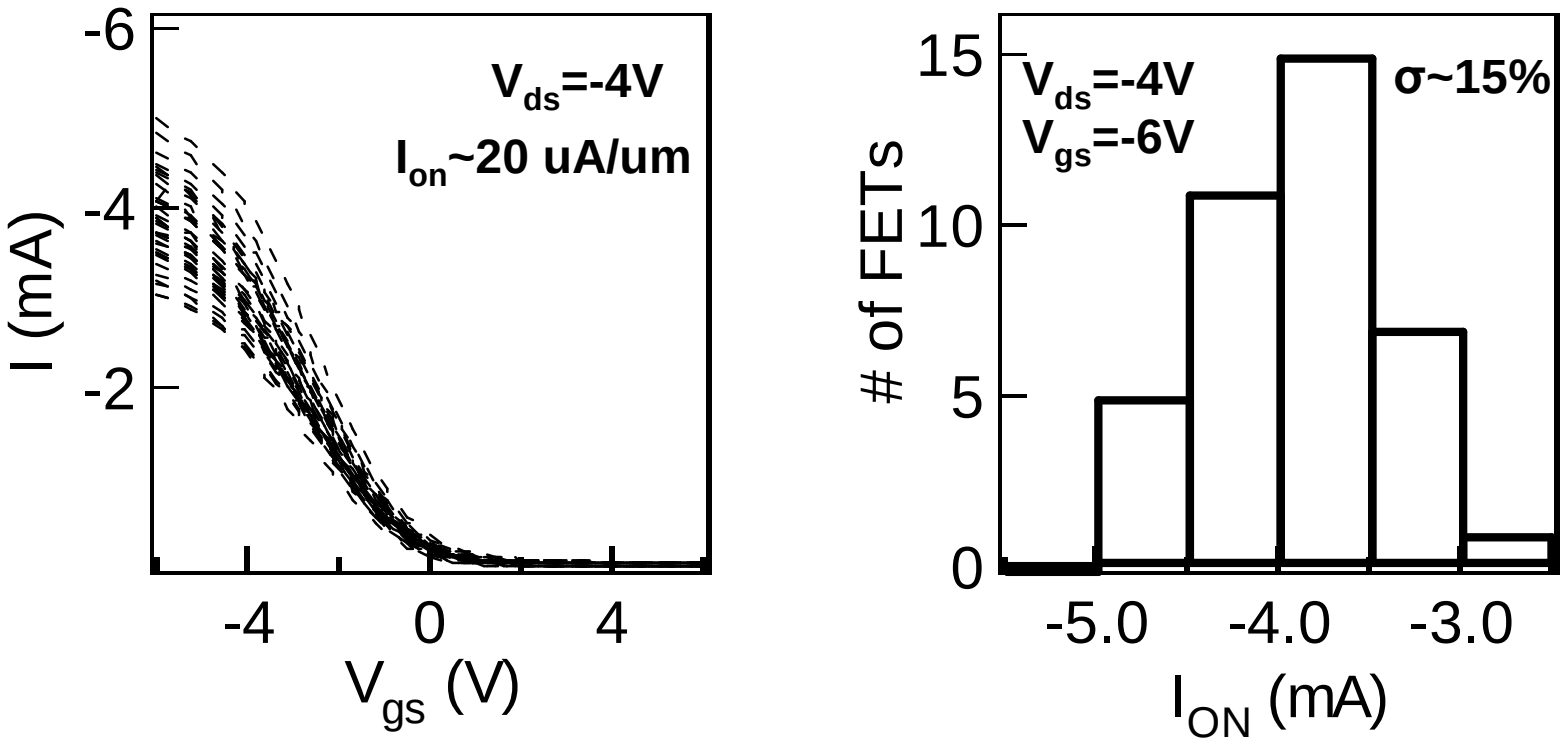
Parallel Array NW Devices





The ON current linearly scales with channel width (number of NWs) due to the uniformity of the printing process.

NW TFT Device Variations

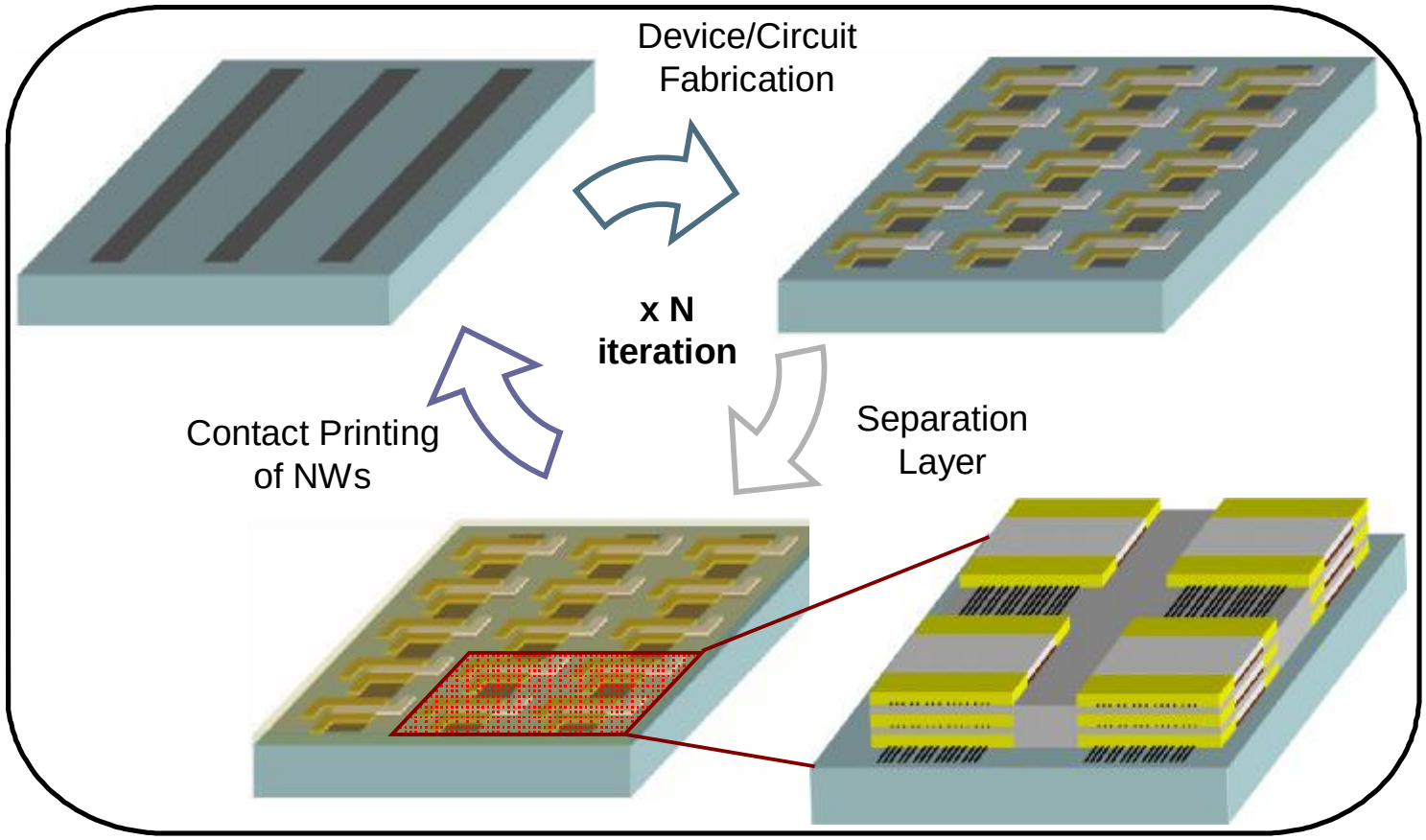


40 separate TFTs on a single layer of a chip

Ge/Si NW d~10 nm, L~2 um, W~200 um, tox (HfO2)~12 nm

Minimal device variation is observed due to the uniformity of the nanowire film.

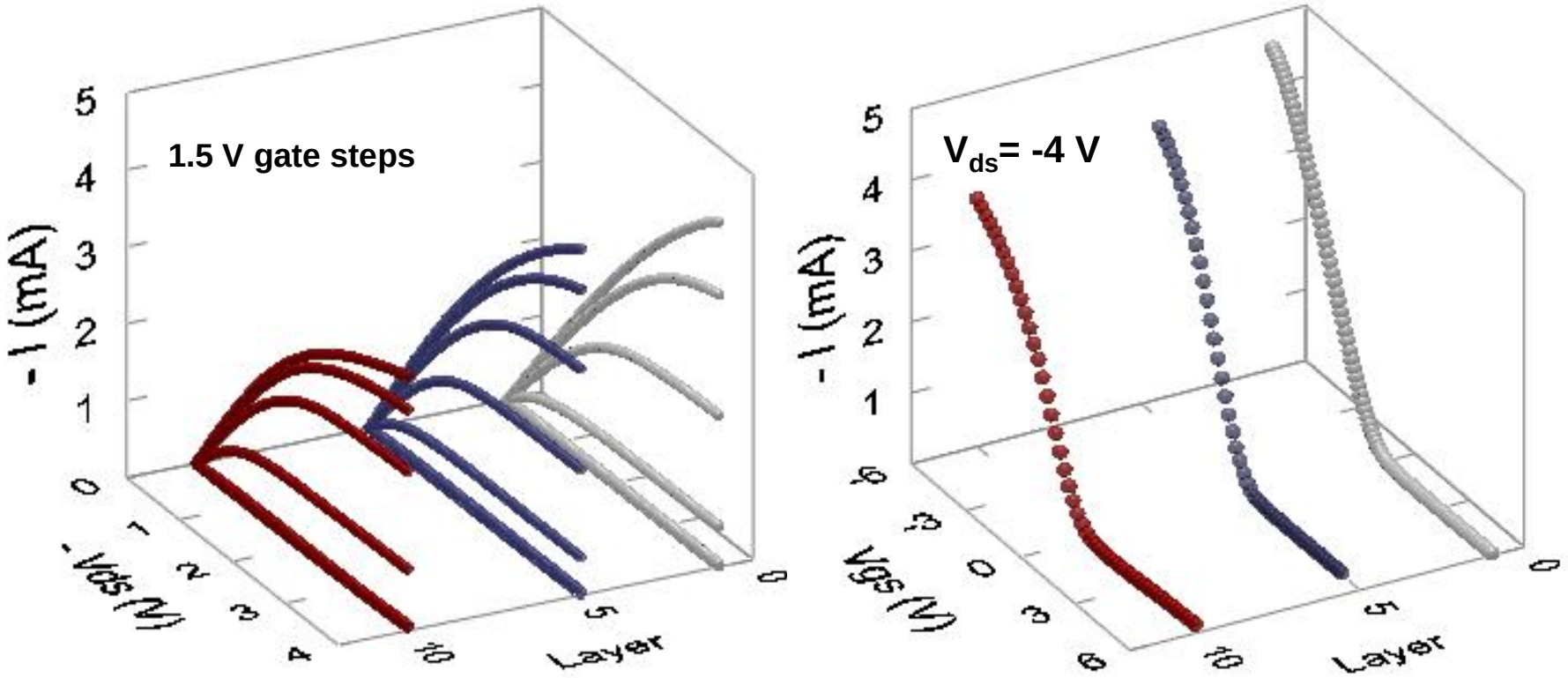
3D Integration of NW electronics



The ease of nanowire assembly on any substrate at ambient temperatures makes them ideal channel materials for future 3D integrated circuits.

Nano Letters, 2007

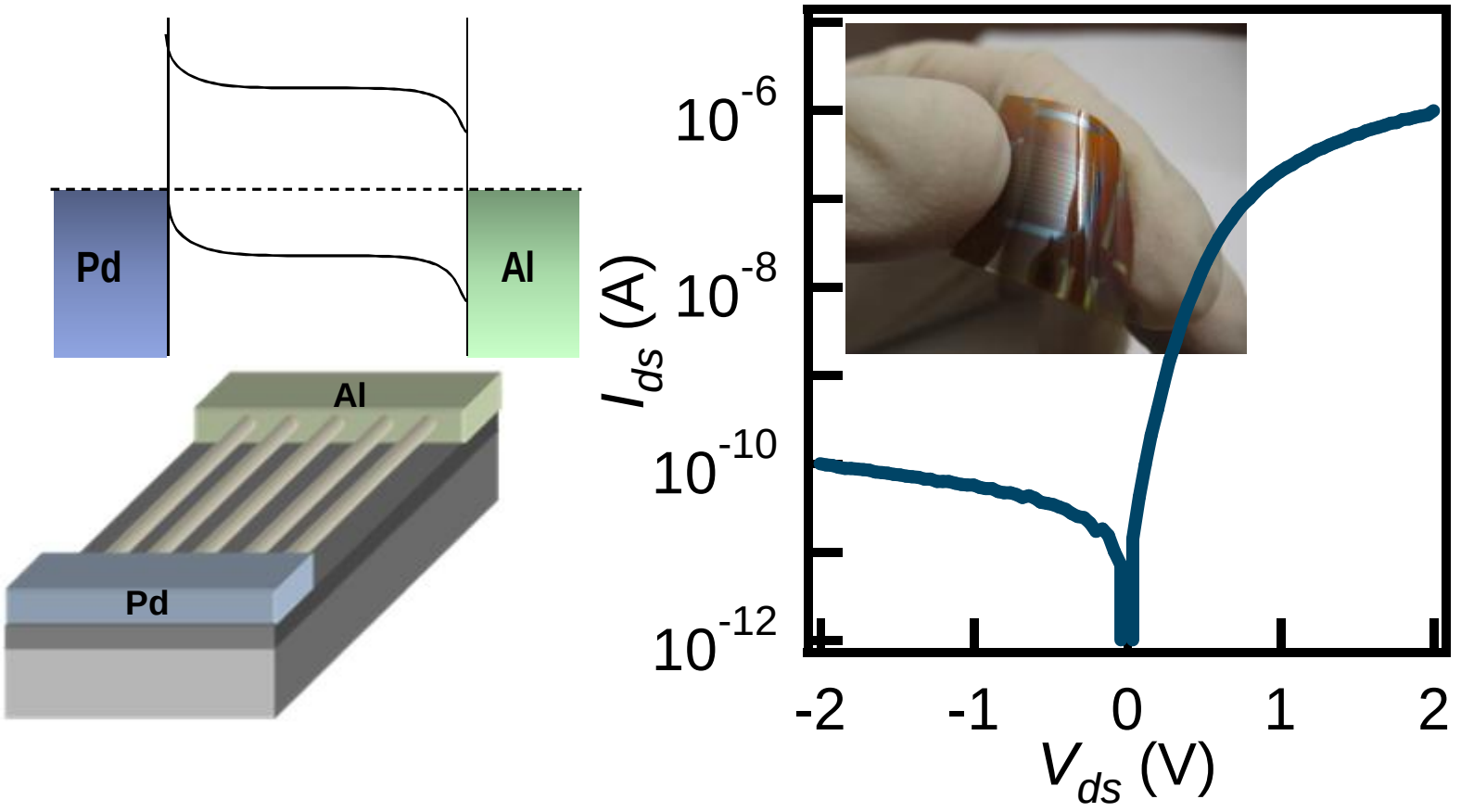
3D Assembly of Nanowire Thin Film Transistors



10 layers of Ge/Si nanowire FETs showing consistent device performance from layer to layer!

d~15 nm, L~2 um, W~200 um, tox (HfO2)~12 nm

Nanowire Schottky Diodes

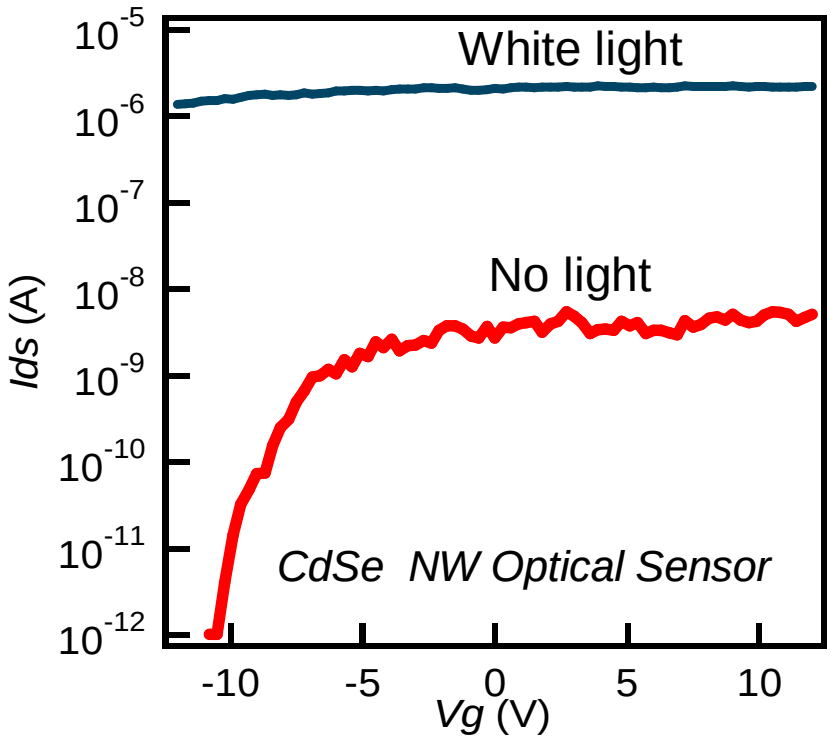


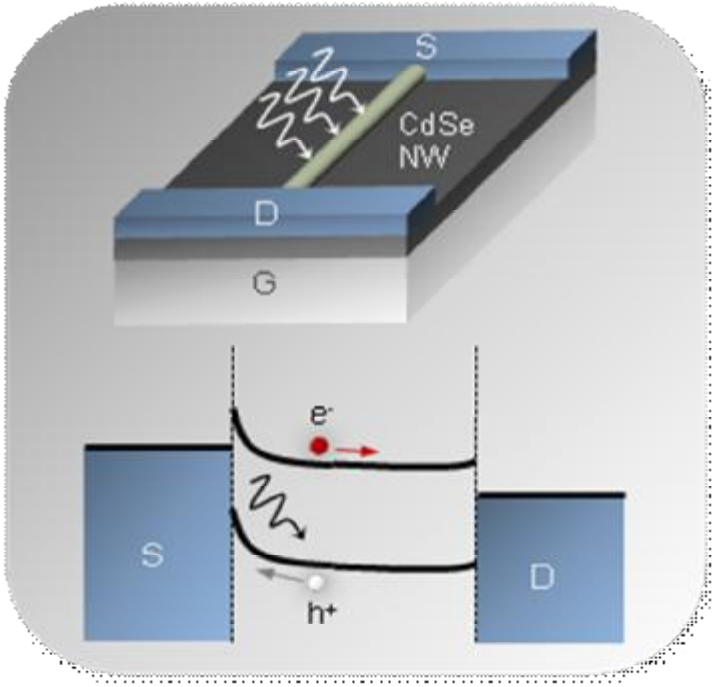
Novel device structures can be explored based on the printed nanowires to meet the desired application needs.

Magnitude of Fermi level pinning needs to be explored.
Are NWs 1D or bulk?

Zhiyong Fan, et al, Nano Letters 2008

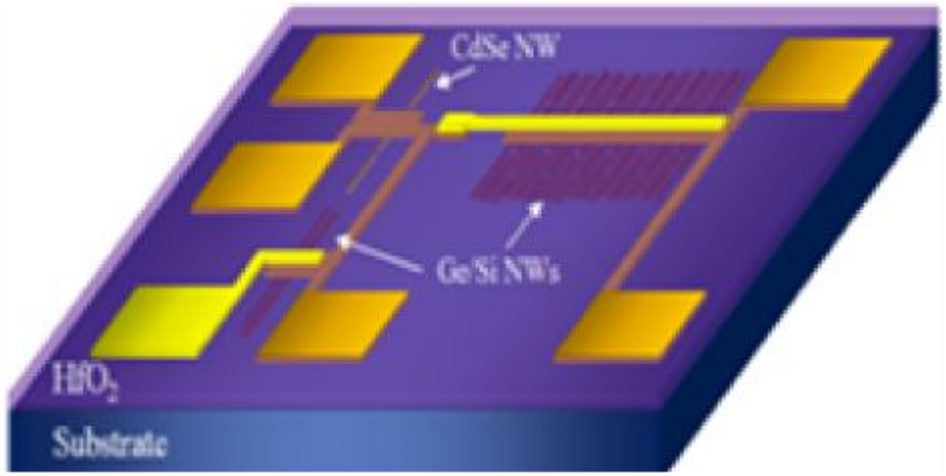
Heterogeneous NW Integration

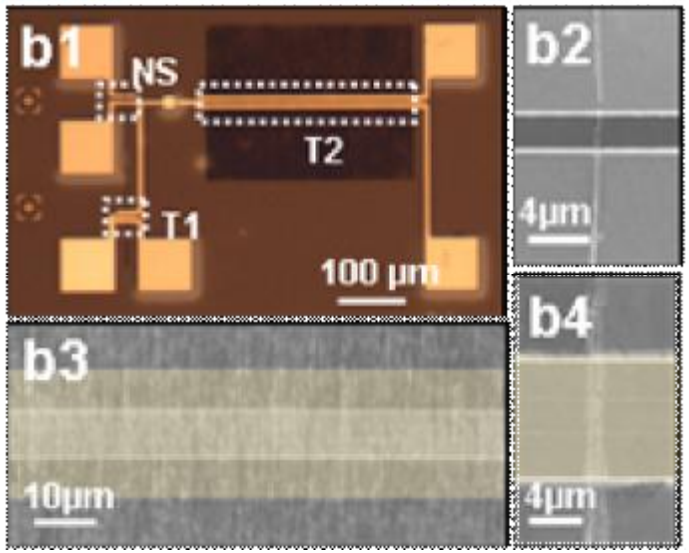




- CdSe NWs as model sensor elements.
- Direct band gap: highly sensitive to radiation exposure

Heterogeneous NW Integration

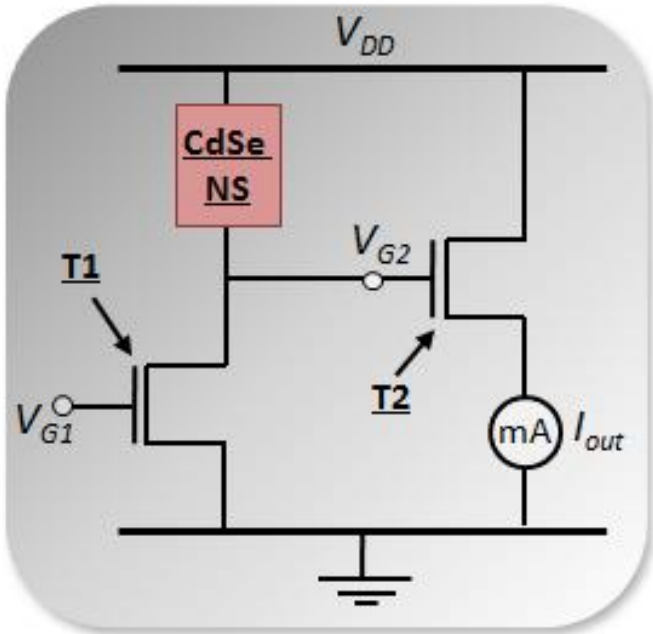




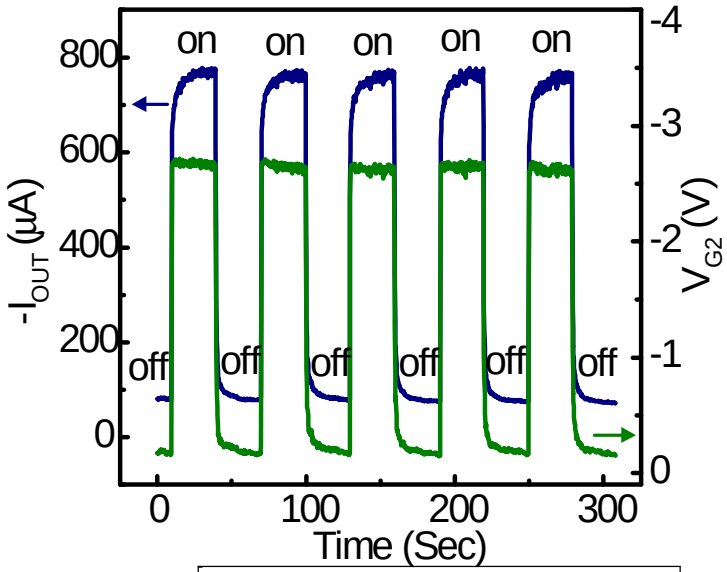
Heterogeneous integration of high mobility Ge/Si NWs with optically active CdSe NWs.

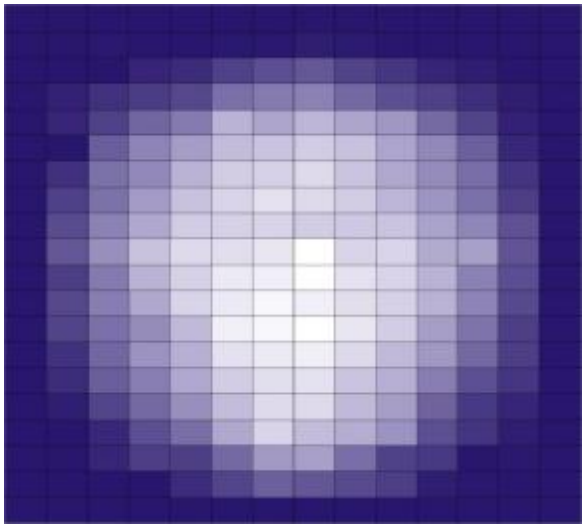
Nanowires are assembled in two printing steps.

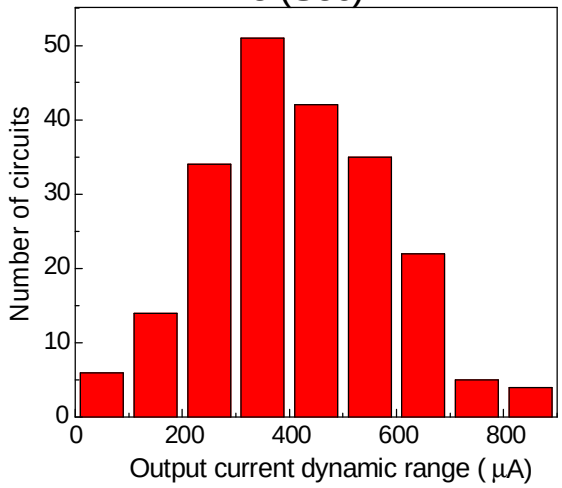
Z. Fan, et al, PNAS, 2008.

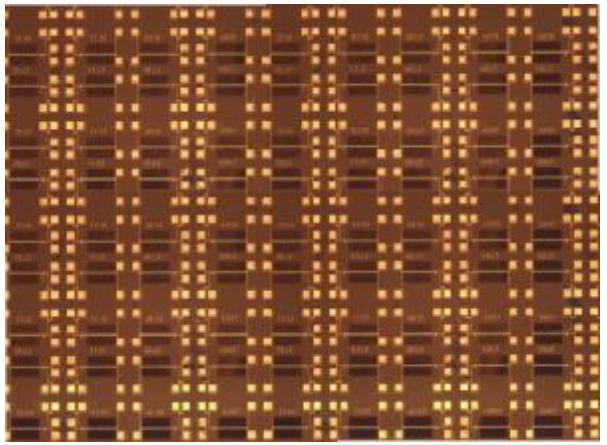


Heterogeneous NW Integration









Proof of concept: large NW arrays can be integrated into functional circuitry with high uniformity over large areas

Summary

- Nanowires are unique building blocks for a wide range of NEMS, sensors, and electronic applications.

- Significant progress in the assembly has been made through the development of a printing technology. Further improvements still needed.

- Heterogeneous assembly of nanowires can be readily attained with high uniformity and over large areas.

Acknowledgements

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