TÉCNICO LISBOA

Nanostructured Materials and Nanotechnologies

Sensor Applications of Carbon Nanotube Field-Effect Transistors (CNT FETs)

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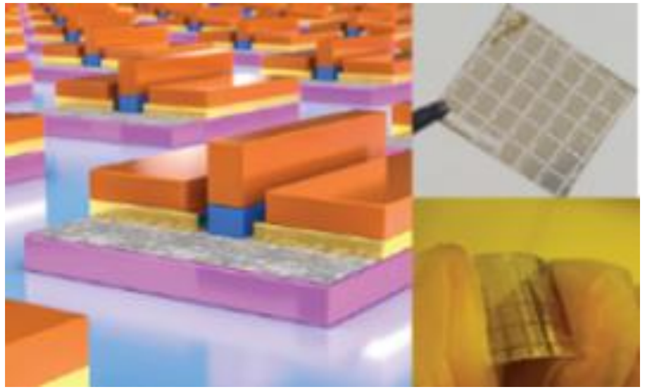
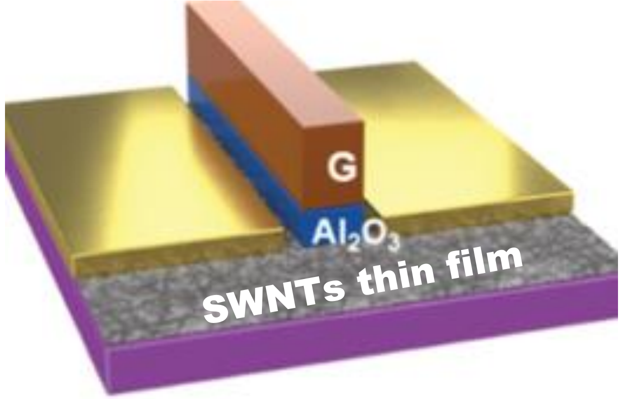
Carbon Nanotube Field-Effect Transistors (CNT FETs)

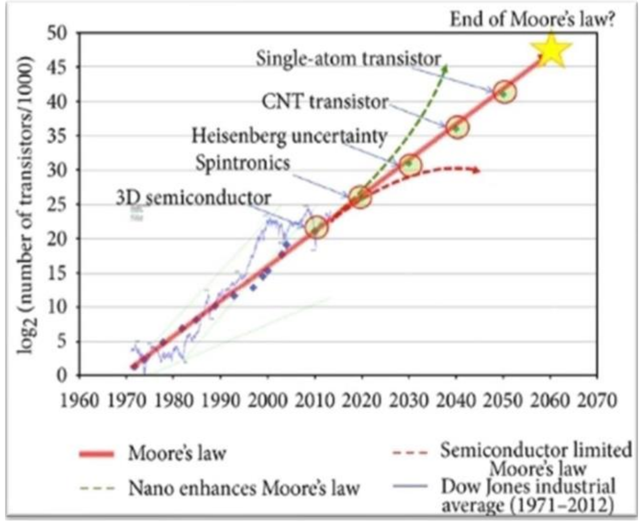
- Scaling of **silicon-based CMOS FETs** → rapid development of microelectronic technology;
  However: physical limit (**shrink devices**), cost and power consumption.
  ⮡ thinner semiconductor materials with higher μ for **smaller and higher-performance transistors**

► **Carbon nanotubes (CNTs)** → great potential to replace silicon ➡ Keep up with Moore's Law

- high performance, low power dissipation, high carrier mobility, higher gain;
- CNT FETs as building blocks for energy-efficient computing technology - emerging **smart sensors**, IoT and cloud technologies;
- recently, 5nm gate length (≈quantum limit of binary switch).

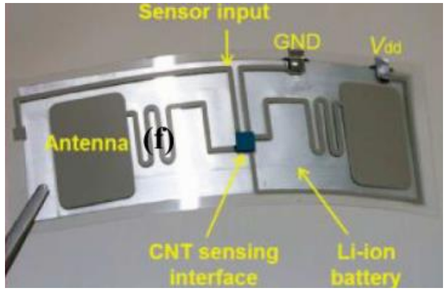






Carbon Nanotube Field-Effect Transistors (CNT FETs)

▶ **Soft and flexible devices** → epidermal sensors (temperature, sweat, motion…) → revolutionize prognosis (fast, cheap and noninvasive).



(CNT IC-based universal interface system of wireless sensors)

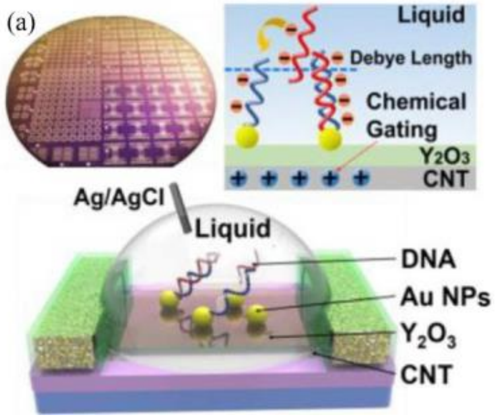
- **However,** susceptible to mechanical/structural damage → lower durability and reduced performance.

→ introduce self-healing capability

▶ **SWCNTs** (single-walled) suitable for flexible/wearable devices (low--power dissipation, excellent mechanical properties – strain);

- Challenges: limited speed, working frequency

▶ CNTs for **highly-sensitive sensors** due to high **surface/volume ratio** (physical accessibility of each atom).



(CNT FETs for biosensor applications)

CNT FET sensors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Field-Effect Transistors

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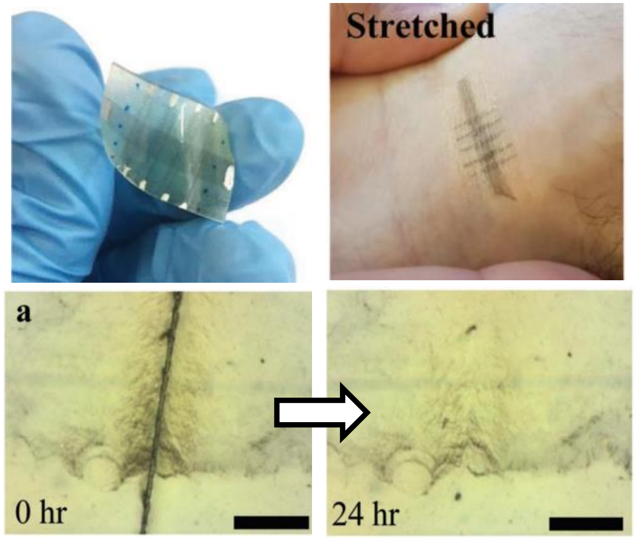
A Freestanding Stretchable and Multifunctional Transistor with Intrinsic Self-Healing Properties of all Device Components

*Muhammad Khatib, Tan-Phat Huynh, Yunfeng Deng, Yehu David Horev, Walaa Saliba, Weiwei Wu, and Hossam Haick**

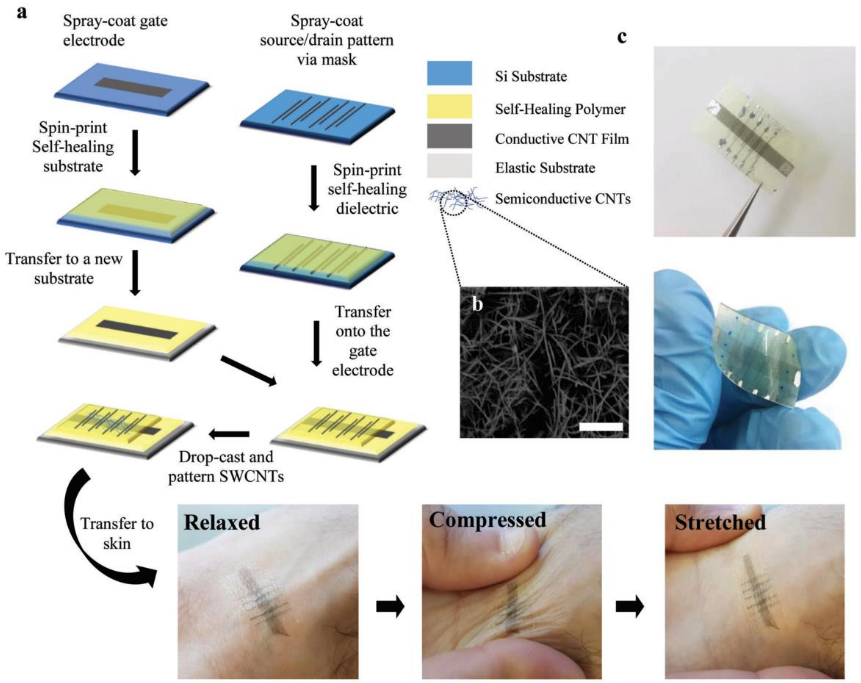


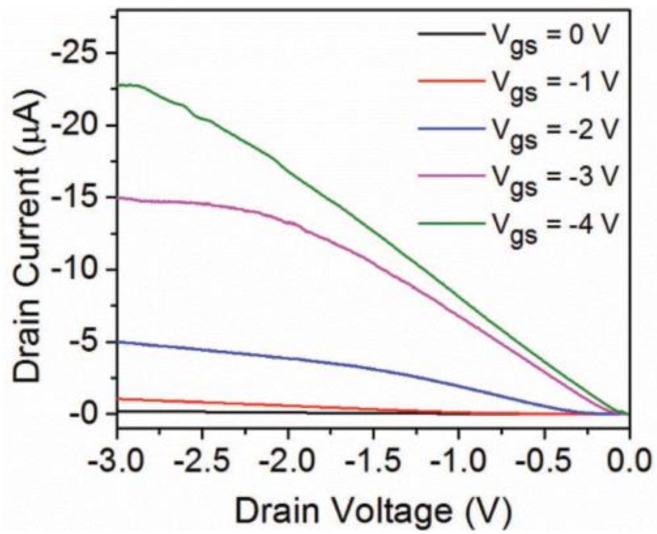
► **This paper reports on carbon nanotubes that empower flexible and stretchable FETs which retain self-healing properties of all FET components. The device:**

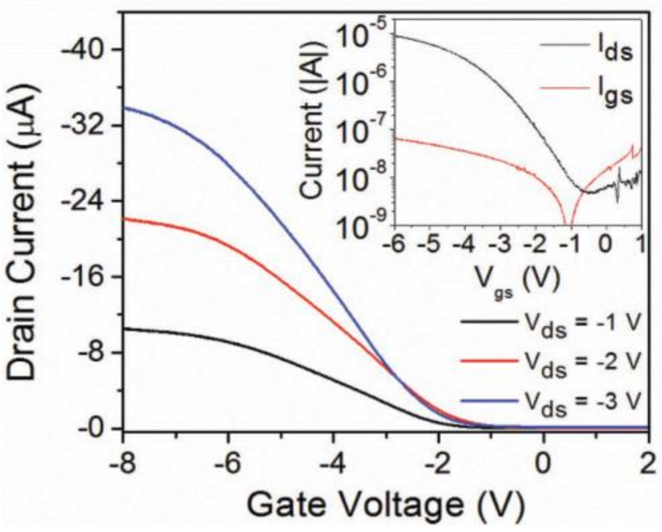
- has repeatable intrinsic and autonomic **self-healing** ability, enabling the restoration of its electrical and mechanical properties, both after microscale damage or complete cut of the device;
- can be repeatedly **stretched** without a significant loss in its electrical properties;
- is applicable in the form of a ≈3μm thick skin tattoo and has multifunctional sensing properties, such as detection of **temperature** and **humidity**.

Fabrication process and device performance

► **PUU** [poly(ureaurethane)] → two monomers; dynamic **hydrogen and disulfide bonds** can break and recover under room conditions without additional energy (**very efficient self-healing material**).





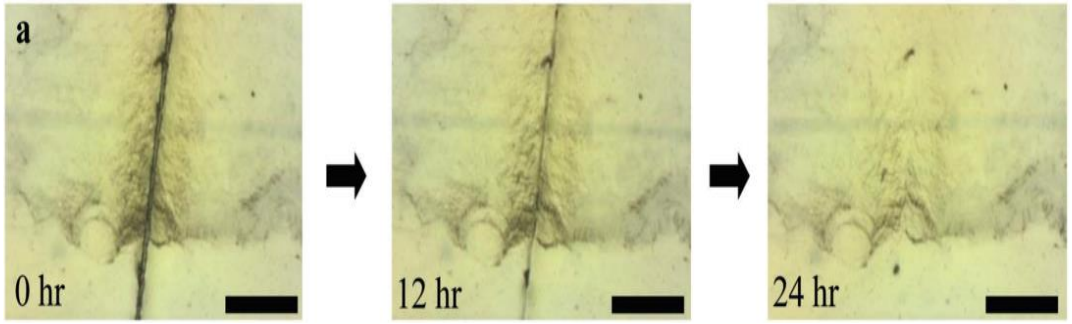


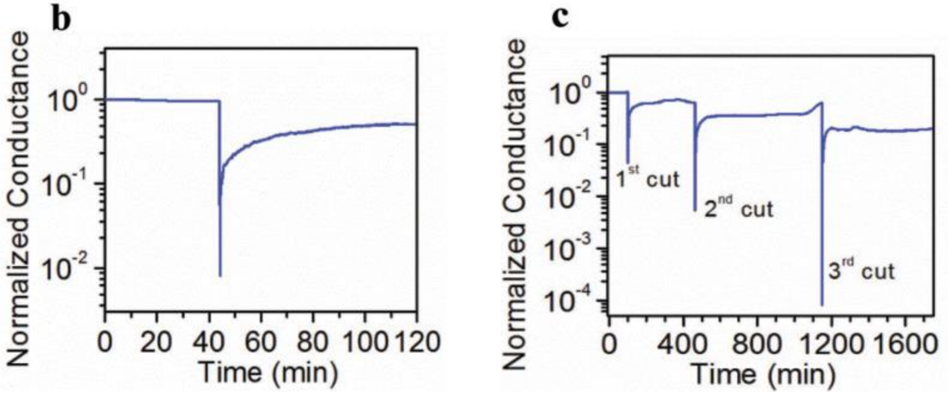
- Top-contact bottom-gate transistors by transfer printing (convenient with self-healing polymers, allows fabrication on human skin).

- Typical output curves of transistor;
- high on-current $I_{on} \approx 30\mu A$, high hole mobility $\mu_h \approx 10\ cm^2V^{-1}s^{-1}$, average on/off ratio $\approx 10^3$.

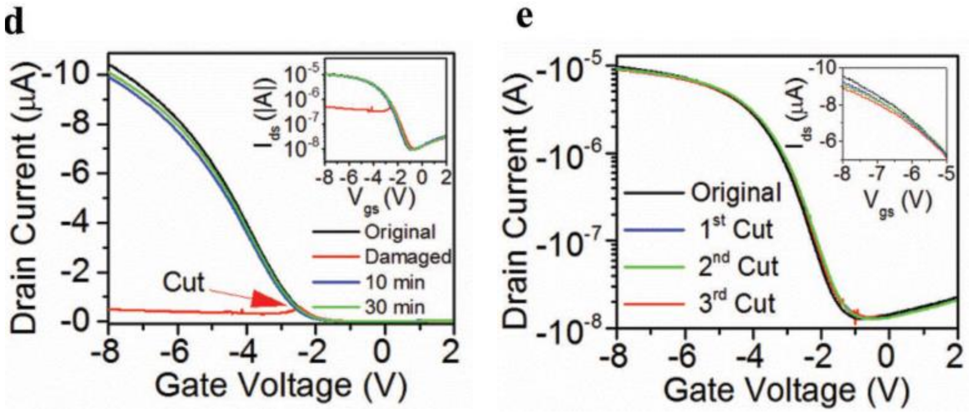
Self-healing ability of the transistor

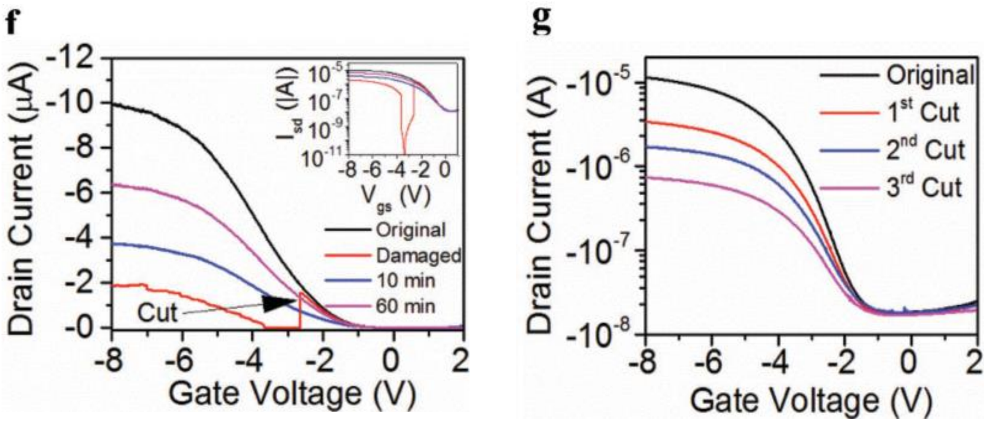
Healing process after a blade-cut perpendicular to the conduction pathway





- Fast initial increase in **conductivity** (recovery of the elastic polymer) followed by slower recovery;

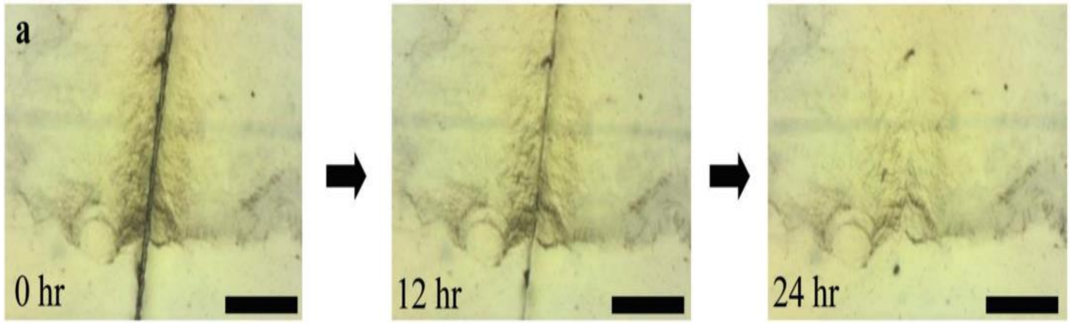




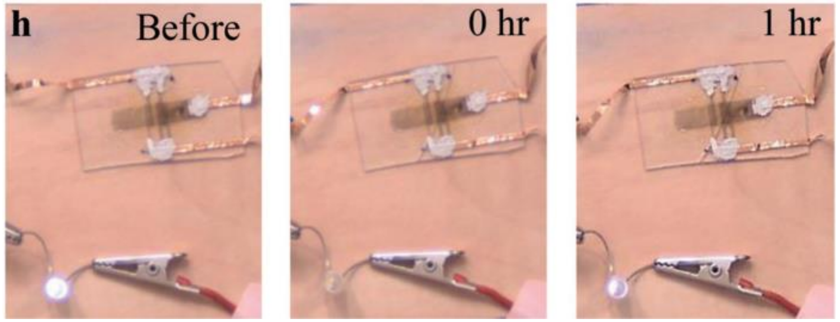
- **Gate damage** prevented further increase in I_D, but recovered after 1h. Gate electrode could heal **several cuts** with negligible change in performance;
- **Source/drain damage** - increase after cut, but lower values than originally after 1h. Several cut cycles could be recovered, but differences are more apparent.

Self-healing ability of the transistor

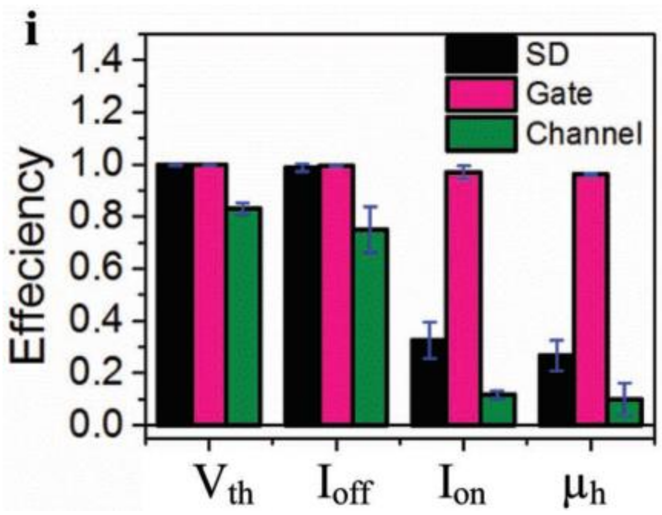
Healing process after a blade-cut perpendicular to the conduction pathway



- **Difference in self-healing of gate and SD electrodes:**
  - ▶ **gate** → polarize dielectric layer, conductivity less important to the performance of the device;
  - ▶ conductivity of **SD** electrodes directly affects I_D, increase in resistance decreases I_D.



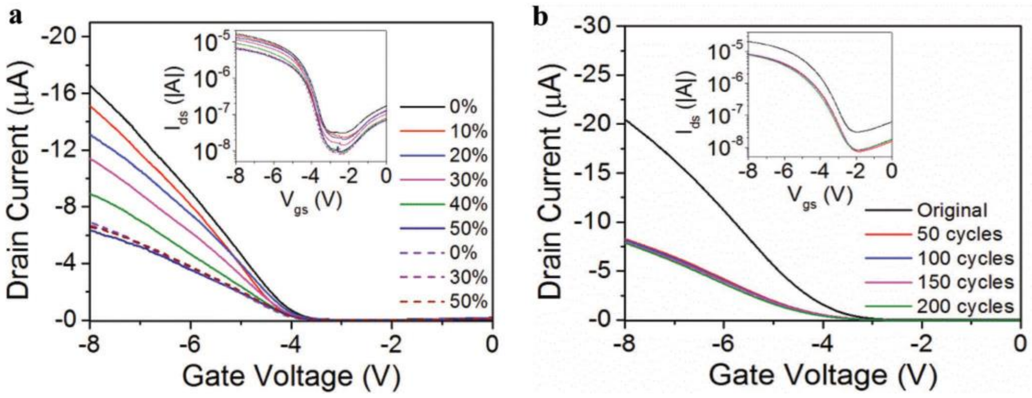
- More severe damage (whole device completely cut). After reconnection, transistor-like behavior recovered after ≈24h (light intensity changed gradually).

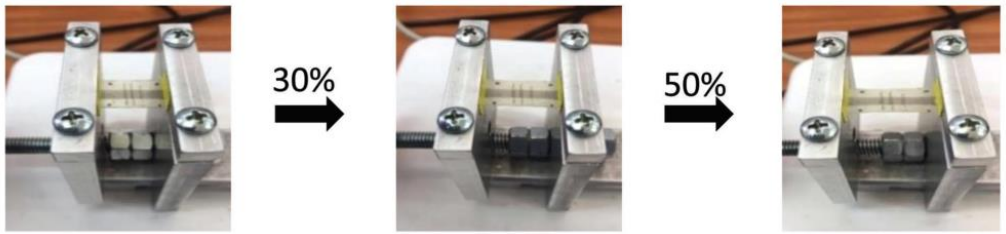


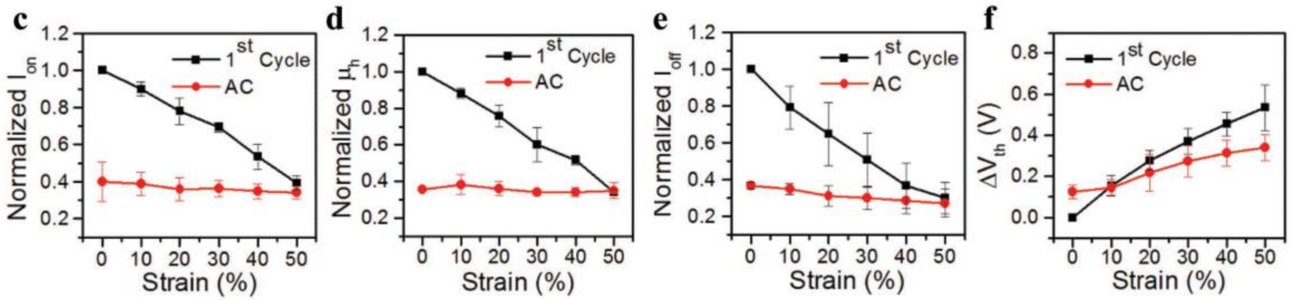
- Efficiency of self-healing evaluated using 4 characteristic parameters:
  - ▶ on-current (I_{on});
  - ▶ hole mobility (μ_h);
  - ▶ off-current (I_{off});
  - ▶ threshold voltage (V_{th}).
- Similar damages in the **channel** very destructive (lower self--healing ability of thinner layers).

Strain-dependent properties of the self-healing device

► Device performance tested under uniaxial strain, parallel to charge transport direction.







- Transfer characteristics for initial **(a)** and later **(b)** stretching cycles of strain up to 50%, applied along the channel length direction;
- **negligible change with increasing number of cycles** after conditioning process (1st cycle).

- Normalized electrical characteristics for stretched devices:

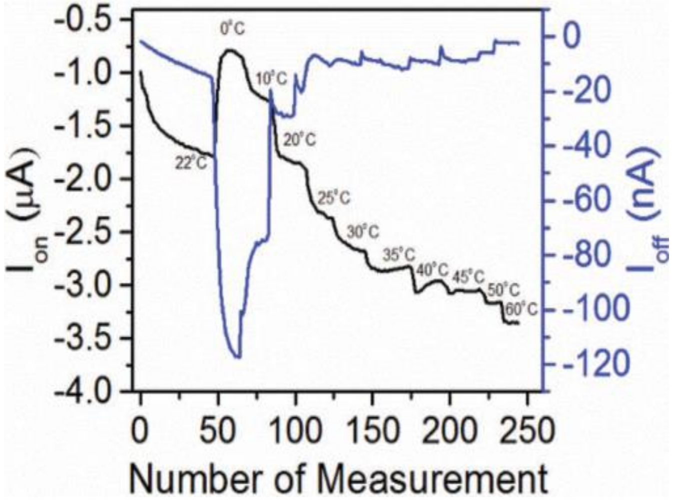
→ I_{off}, I_{on} and μ_h decreased by up to ≈60%;

→ V_{th} slightly shifted to more negative values as strain increased.

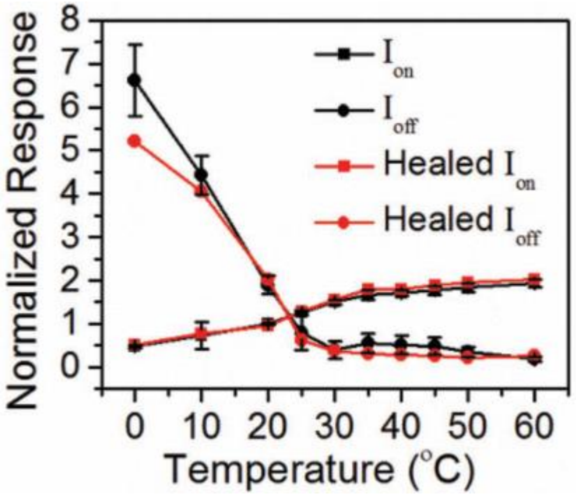
► **V_{th}** maintained **some sensitivity** to strain (decrease in capacitance with increasing strains). **Strain-dependent <u>and</u> strain-independent** parameters is desirable → multifunctional devices to detect different stimuli (e.g., **strain**, **temperature**, **humidity**) - without complicated data processing to separate the responses to each type of stimulus.

Transistor-based self-healing applications

► **Responses of the FET to <u>temperatures</u> from 0 to 60 °C:**



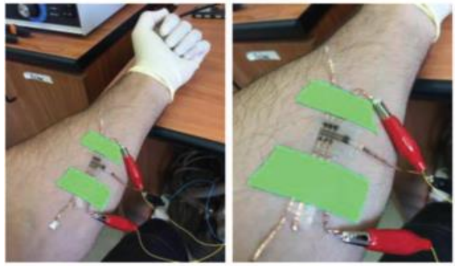
- I_{on} and I_{off} **biggest changes** in **lower temperatures** (limit polymer mobility/softness and decrease gate modulation ability);
- **higher temperatures** → **lower** $\mathbf{V_{th}}$ values;
- sensing ability conserved after healing of structural damage.



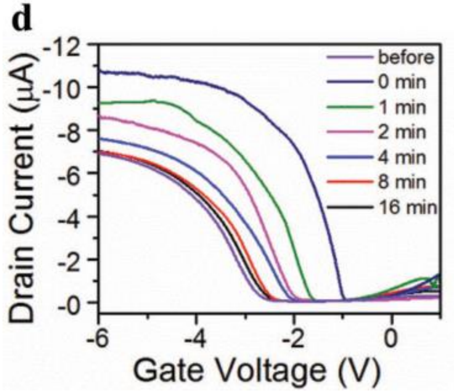
► **Potential to sense <u>humidity</u> values or <u>hydration levels</u> of the skin:**

- **Elasticity** and **capacitance** of PUU12 (polymer) highly affected by humidity;
- humidity values from 0% to 100% → devices showed lower $\mathbf{V_{th}}$ and higher $\mathbf{I_{on}}$ under **higher humidity** values.

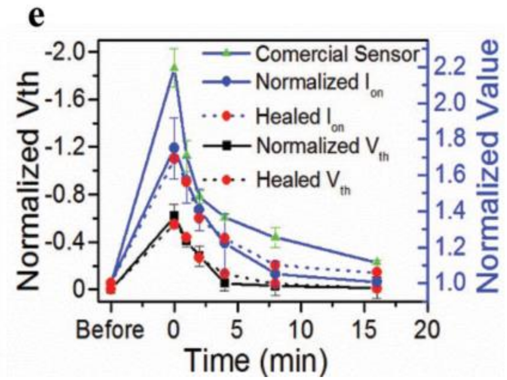
Transistor-based self-healing applications



Self-healing FET as epidermal skin for humidity detection



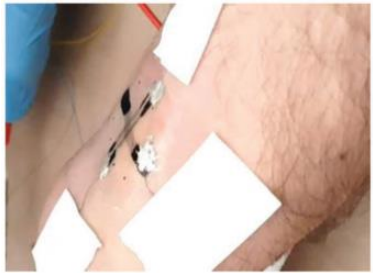
- Transfer curves obtained at different times after skin humidification;



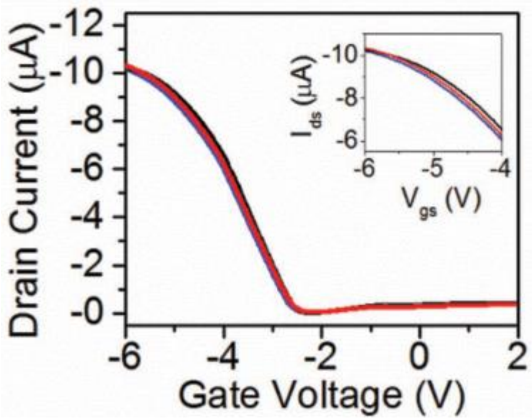
- V_{th} and I_{on} decrease after humidification and approach original values;
- same behavior after self-
  -healing of the sensor.

Application to skin as ultrathin tattoo (≈3µm thick)

- ✓ highly promising for future **diagnostic applications**;
- ✓ attachment of the sensor only due to van der Waals interactions and without using any adhesives.



- Performance tested under different skin strains;
- stable, with very negligible changes in different hand positions.

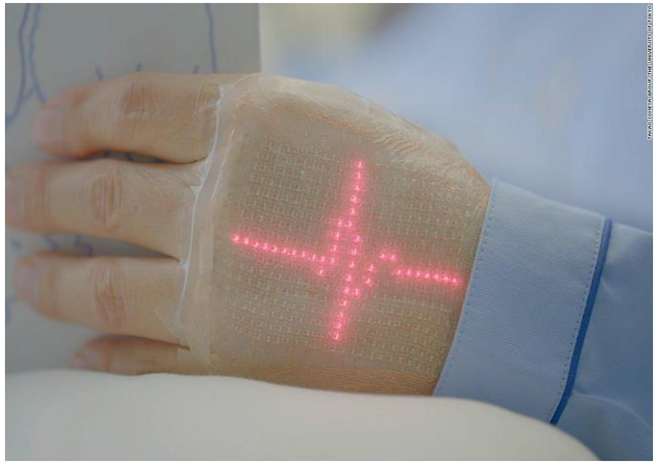


Conclusion

► **First autonomic self-healing and stretchable FET using self-healing PUU as a host matrix filled with CNTs**

- ✓ recovers from varying **mechanical damage**;
- ✓ can be stretched for >200 cycles of up to 50% **strain** without significant loss in electrical properties;
- ✓ self-healing and high stretchability improve its **lifetime**;
- ✓ multifunctional sensor that detects **temperature** and **humidity**;
- ✓ **ultrathin tattoo** → *in situ* analysis of skin environments for personalized and continuous investigations.

- Raises expectations that **flexible and stretchable devices** might become fully autonomic, thus increasing their lifetime and reliability in several applications, such as e-skin and wearable electronics. The integration of self--healing will increase sustainability of electronic systems, leading to more **environmentally friendly** applications.



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