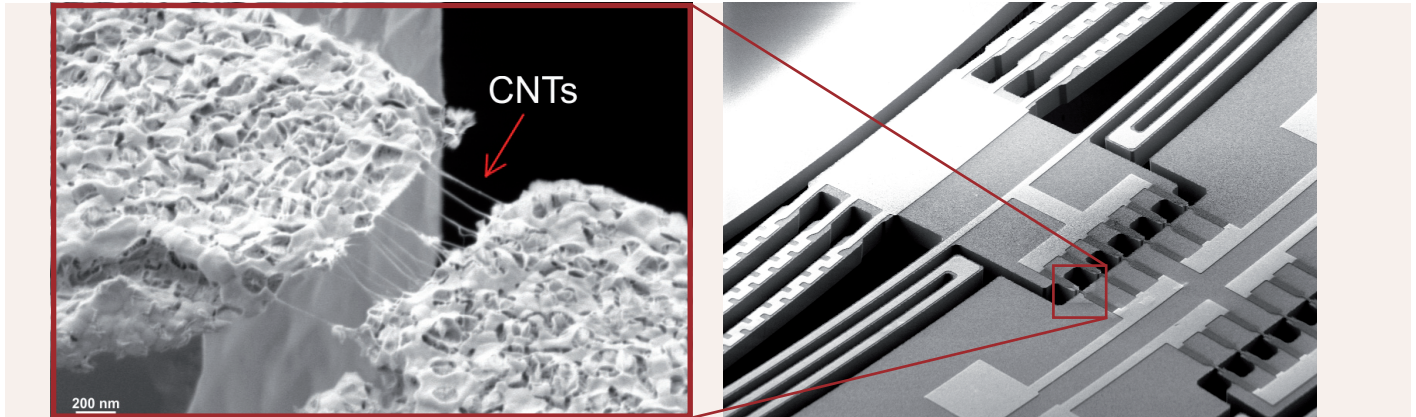


SCALING UP INTEGRATION OF CARBON NANOTUBES INTO MEMS



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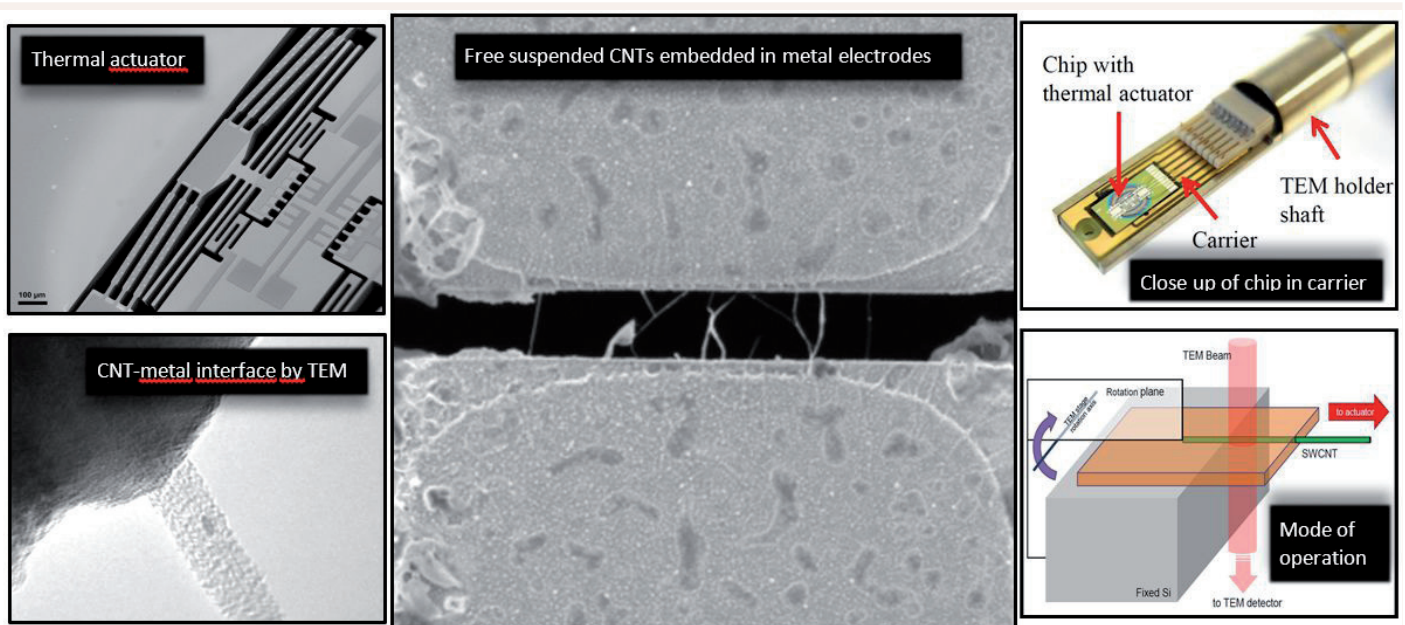
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All information contained in this datasheet is preliminary and subject to change. Furthermore, the described systems, materials and processes are not commercial products.

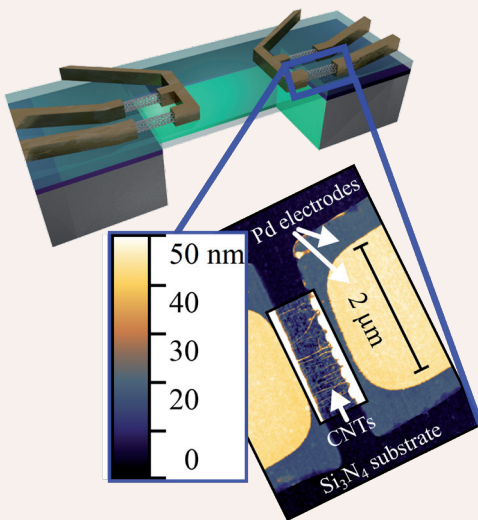
Pronounced trends like Industry 4.0, the Internet of Things or flexible electronics obligate new and innovative approaches for scalable fabrication of electronics and sensors using novel functional nanomaterials like single-walled carbon nanotubes (SWCNTs). The outstanding intrinsic properties of SWCNTs such as superior mechanical strength and piezoresistivity facilitate a new class of miniaturized strain sensors standing out by sensitivity and flexible integration scenarios. Here we demonstrate at the example of two feasibility studies a hybrid technology fusing conventional MEMS and CNT technology. Following a holistic wafer-level approach, we demonstrate the potential of CNT-based sensors by ultra-sensitive detection of smallest displacements on membranes in MEMS pressure sensors going beyond SoA sensitivity factors. Moreover, a CNT-MEMS is presented containing suspended SWCNTs clamped into a MEMS test platform enabling fundamental studies on sensors and reliability, on the one hand and demonstration of new building blocks in future MEMS/NEMS such as ultra-high frequency detection in condition monitoring applications, on the other hand.

CNT-based strain sensor

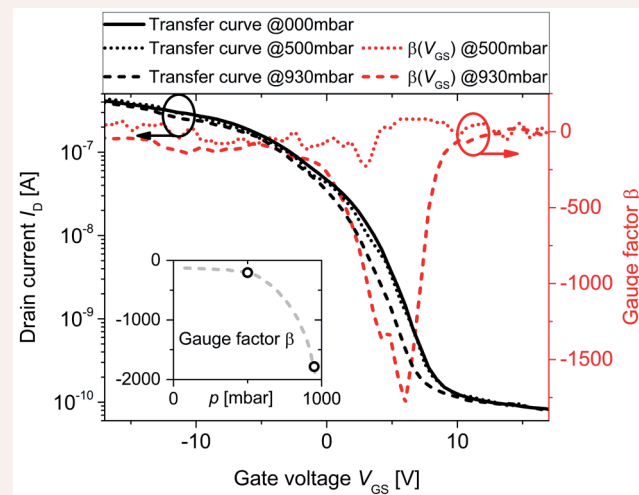
In order to explore and systematically study the giant piezoresistivity we envisage sensor architectures with integrated SWCNTs in classical MEMS like membrane based pressure sensors. The wafer-level nano-manufacturing process chain implements a scaled-up electrokinetic approach for aligned SWCNT assembly. For extended studies on sensor characteristics, the sensor was operated in field-effect transistor (FET) configuration using the Si membrane as a gate. The transfer characteristics of the CNT-FET upon pressure actuation are shown in Figure page 2 (right). At the working point of the CNT-FET at $V_{GS} \sim 4 \text{ V}$ the conductance is significantly reduced shifting the transfer curve to lower gate voltage indicating on a bandgap opening of the SWCNT under strain. The corresponding strain was determined from finite element simulations to be 0.13 % at CNT site allowing to calculate the absolute gauge factor $\beta = [R_0 - R(\epsilon)] / R_0 - 1 \cdot \epsilon^{-1}$ with respect to the reference strain state at 0 mbar. This revealed a maximum absolute gauge factor of $\beta \sim 1750$, which is about one order of magnitude higher than for commercial available strain gauges.



Graphical abstract for in situ TEM testing of interfaces between carbon nanotubes and metals.



Schematic of the fabricated sensor structures with zoom-in AFM images of the CNT-FET revealing homogeneous assembly of individual, fully embedded SWCNTs (channel area not to color scale).



Transfer characteristics ($V_{DS} = 100$ mV) of the CNT-FET upon pressure actuation (black) together with the corresponding gauge factor (red). Inset shows non-linear dependence of β on induced strain.

MEMS with suspended CNTs for reliability studies

Understanding the mechanical interface behavior of SWCNTs embedded in a metal contacts is crucial for the establishment of a reliable technology for high-sensitive mechanical CNT sensors. The assessment of interface strength and critical forces is an important issue to prevent sensor damage or failure. In previous investigations we determined maximum forces in the range of 10 to 102 nN and rupture as dominant failure mode of CNTs embedded in Pd.

To get more detailed information about interface parameter like SWCNT diameter and embedding length or even number of defects contributing to the pull-out process we present a MEMS-based test stage for in situ TEM experiments to study interfaces between CNTs and embedding metals, while applying an external pull out load and monitor the detailed atomistic processes at the interface. Using a holistic wafer-level technology, free suspended CNTs are integrated in the MEMS test stage in the form of a thermal actuator. Technological key parameters for homogeneous

and reproducible CNT assembly like CNT pre-selection by length separation and their integration by dielectrophoresis are addressed as well as an appropriate contact formation procedure. TEM experiments on actuators with suspended thin metal electrodes allowed atomic resolution and the actuator shows stable movement in the focal plane for different actuator displacements. Moreover, we applied successfully digital image correlation to TEM images (TEM-DIC) for strain determination.