Electronic Supplementary Material (ESI) for Physical Chemistry Chemical Physics.

Supporting Information

Remote Joule Heating Assisted Carrier Transport in MWCNTs Probed at Nano-second Time Scale

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Nano-Second Pulse I-V Setup and Device Characterization

A. Pulse Generation: Fast rising signals at the time scale of nano-seconds consist of high-frequency components. Wavelength of such signals is comparable to length of various parts of test equipment. Consequently, conventional methods cannot be used for their generation and transmission. Keeping this vital concept in mind, a different strategy was employed to generate fast rising signals at the time scale of nano-seconds. Signals were generated through two 50 Ω matched transmission lines connected with a switch S_1 (Fig. 1). At $t<0$, transmission line TL_1 is charged to a pre-defined voltage V_0. At $t=0$, switch S_1 is put to closed state, which results in propagation of $\frac{V_0}{2}u(t)$ and $\frac{-V_0}{2}u(t)$ (reflection) in opposite directions at the switch. Eventually, both the waves superimpose to give a rectangular pulse of amplitude $\frac{V_0}{2}$ and where the pulse width (PW) given by:

$$PW = \frac{2L}{v} \approx \sqrt{\varepsilon_r}\frac{2L}{c}$$

where, $2L$ is the combined length of TL_1 and TL_2, v is the speed of wave propagation in the transmission line, c is the speed of light, and ε_r is the relative permittivity of the transmission line medium.

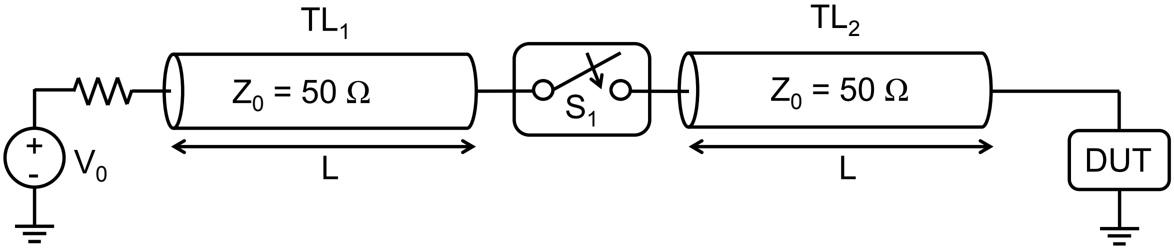


Figure 1: Nano-second long pulse generation through transmission lines

B. Voltage and Current Measurement at Nano-second Time Scale: Measurement cycle of a conventional source measurement unit lies in the range of few hundred micro seconds. Consequently, these units are not capable of measuring voltage and current signals changing at the time scale of nano-seconds. In our measurements, this issue was bypassed by directly capturing the voltage signals using high band-width sampling oscilloscope (MDO 4104B6 from Tektronix, Resolution = 1mV/div). Current was sensed by using a high bandwidth current transformer (CT1 from Tektronix, 1 GHz, sensitivity = 5mV/mA). A basic current transformer consists of primary and secondary coils separated by core. Transient change in current at primary side induces a magnetic field, which in turn induces

AC current in secondary coil. The secondary coil is terminated at 50 Ω port of the sampling oscilloscope. The 50 Ω resistor converts the AC current to corresponding voltage, which is then captured by sampling oscilloscope.

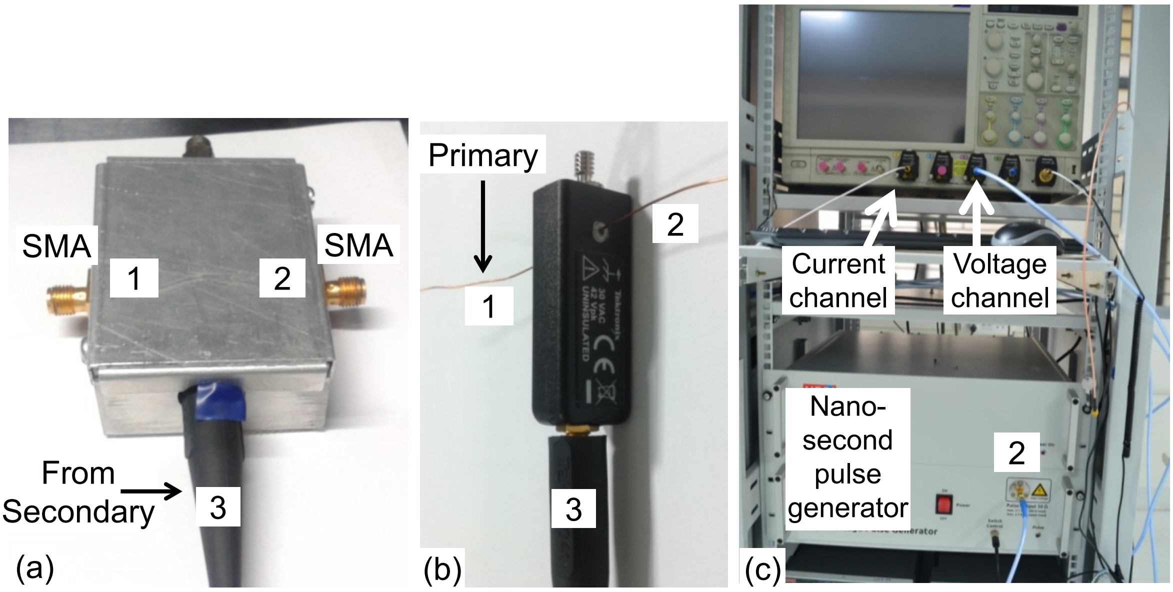


Figure 2: Voltage and current sensing at nano-second time scale. (a) 3-port current sensor. Port 1 connects to the force probe, port 2 connects to the output of pulse generator and port 3 is connected to the current channel of the oscilloscope. (b) Inner body of the current sensor shown in (a). A wire connecting port 1 and 2 runs through the core and serves as primary coil. (c) Voltage channel of the oscilloscope gets signal directly from the sense terminal (not shown in the figure). Blue colour wires are semi-rigid SMA-terminated co-axial transmission lines (Sucoflex 104P).

C. System Calibration: Accuracy of high frequency measurements depend on reflections (in transmission lines and at interfaces) and parasitic impedance. These two factors were taken into account by calibrating the entire system against standard reference values. Calibration was done in the following sequence:

1. Time axis of both voltage and current channels were adjusted to have zero offset in time.
2. Voltage channel was calibrated against the breakdown voltage of a reference SMD zener diode (V_{BD} = 5.18 V).
3. Current channel was calibrated against the resistance of a reference SMD resistor (99.716 Ω).

Above sequence was fired before starting any new set of measurement and it was ensured that the system performs exactly same during all sets of measurements.

D. Wafer Level / On-Chip RF Probing: Devices were probed using RF probes in Kelvin / 4-wire architecture. Special 50 Ω terminated GS probes were used to separately force and sense signals through the device. This architecture ensured – (a) minimal noise due to system parasitic impedance, (b) 50 Ω matched RF environment throughout (metal contact to source impedance of TL_1), (c) RF shielding of the transmission line from source impedance of TL_1 to landing probes. Probing was done inside a probe station sitting on an active vibration isolation table, which in turn suppressed the ambient mechanical noise.

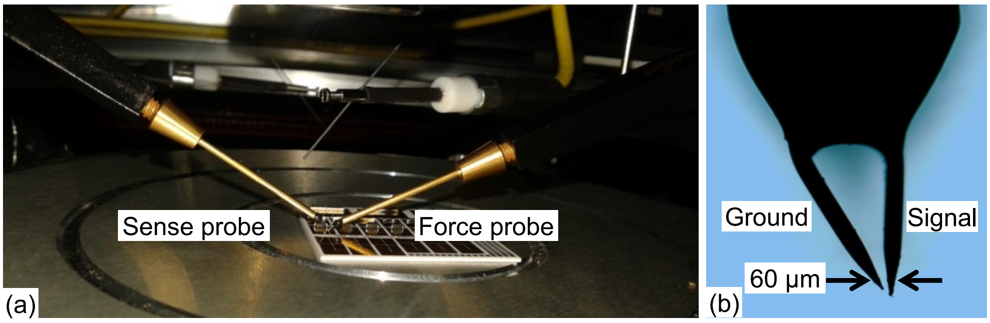
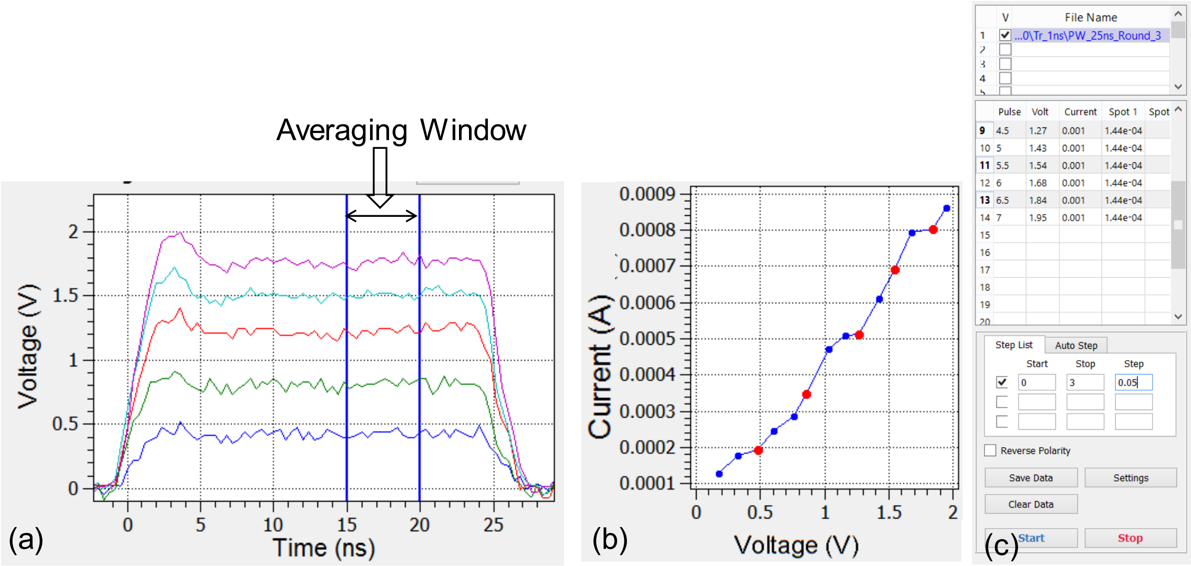


Figure 3: (a) RF (GS) probes arranged for Kelvin 4-wire probing. Probes have 4 degrees of freedom (b) Magnified view of the probe. Black part protruding out of the probe is a 50 Ω resistor.

E. System Control and Automation: Automatic control of all the equipment, system calibration and data acquisition was done using a Python program (Fig. 4).



	V	File Name
1	☑	...0\Tr_1ns\PW_25ns_Round_3
2	☐	
3	☐	
4	☐	
5	☐	

	Pulse	Volt	Current	Spot 1	Spot
9	4.5	1.27	0.001	1.44e-04	
10	5	1.43	0.001	1.44e-04	
11	5.5	1.54	0.001	1.44e-04	
12	6	1.68	0.001	1.44e-04	
13	6.5	1.84	0.001	1.44e-04	
14	7	1.95	0.001	1.44e-04	
15					
16					
17					
18					
19					
20					

	Start	Stop	Step
☑	0	3	0.05
☐			
☐			

☐ Reverse Polarity

Figure 4: (a) Control software's window depicting voltage waveforms captured at the oscilloscope and sensed using the sense RF probe across the device. The averaging window is the range in which data / acquired samples were averaged to produce a single data point of the pulse I-V characteristics depicting in (b). (b) Pulse I-V characteristics of some device. (c) Pulse I-V control window to define range of pulse voltage, fire measurements and saving data.