Single-Walled Carbon Nanotube Mixers

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***Abstract* — We report fabrication and experimental characterization of metallic single-walled carbon nanotube (SWNT) mixers. Metallic nanotubes attached to gate dielectric (SiO_2) and suspended nanotubes were fabricated over Poly-Si gate structures. Devices were characterized for their RF mixing performance up to 80MHz. Under identical input signals, the suspended nanotube mixers had about 8 to 13dB higher convergence gain than the devices attached to the gate dielectric. The advantages of using patterned Poly-Si gate for RF mixers are low parasitic capacitance from the pad to SWNT contacts, and compatibility of Poly-Si gate material with subsequent high temperature growth of SWNTs.**

***Index Terms* — Carbon nanotube, convergence gain, metallic nanotube, mixer, nanotechnology, poly-silicon, single walled.**

I. Introduction

Carbon Nanotubes are rolled-up sheets of graphitic Carbon available in both single- and multi-walled forms. Due to their unusual one-dimensional crystalline structure, carbon nanotubes have exceptional physical, electrical and mechanical characteristics [1]. Near-ideal one-dimensional crystalline structure results in ballistic electron/hole transport inside single-walled carbon nanotube (SWNTs)[2]. Therefore, electronic devices that utilize the transport properties of SWNTs have the potential to operate at extremely high frequencies. For this reason, carbon nanotube devices are among the most promising candidates for future nano-integrated circuits.

Despite near-ballistic conduction, application of SWNTs in high frequency devices and circuits is hampered by intrinsic high input impedance of these devices in the presence of relatively high parasitic capacitance. The parasitic capacitance is due to nanotube contact metallization and is typically in the range of fF to pF. The high impedance of the nanotube (kΩ to MΩ) generates time constants (psec to µsec) that dominates the short transit time of electrons and holes flowing ballistically inside the nanotube (fraction of psec). Nevertheless, by optimizing the nanotube device structur for high frequencies and by controlling the nanotube synthesis, one can achieve acceptable RF performance.

The RF performance of carbon nanotubes have been recently reported by our group and others [3]-[6]. In [3], high quality factor mechanical resonator using suspended carbon nanotubes is reported. Modulation of electrical conductance of the nanotube with the mechanical vibration is measured at tens of MHz. In [4], a carbon nanotube FET device is measured in an LC tank at 2.6GHz. By resonating out the parasitic capacitance of the nanotube with an inductor, conductance modulation has been detected at 2.6GHz resonance frequency. Through using patterned Poly-Si gate fingers, our group has reduced the parasitic capacitance facing the nanotube. We have reported a multi-finger carbon nanotube transistor with a cut-off frequency of 2.5 GHz [5]. We have also reported a 12MHz frequency doubler using a suspended metallic carbon nanotube [6].

In this work, we have synthesized and fabricated mixer devices based on metallic single-walled carbon nanotubes. A combination of suspended nanotube structure and patterned poly-Si actuating gate finger is used to reduce the overlapping parasitic capacitance of the device. This has enabled us to detect the mixing signals at high frequencies. The nanotubes are clamped on two sides (RF and IF ports) and are actuated using a poly-Si actuation pad (LO port). We have compared mixing performance of nanotubes that are attached to SiO_2 gate dielectric with those that are suspended about 0.5µm above the actuation pad. The schematic of the suspended nanotube device is shown in Fig. 1. The RF mixing performance of nanotube mixer devices are experimentally measured up to 80MHz using an Agilent 4408 spectrum analyzer and a Picoprobe active probe.

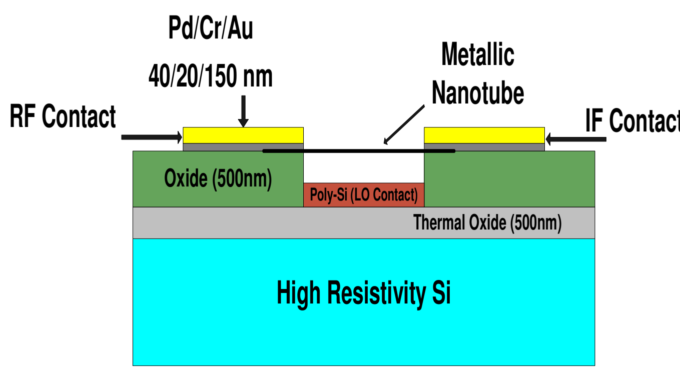

Fig. 1. Suspended single-walled nanotube mixer.

II. Fabrication

In this section, the fabrication process of suspended carbon nanotube mixer is explained. The devices are fabricated on a high resistivity silicon wafer coated with 500 nm thermal SiO_2. 300 A° LPCVD poly silicon is deposited at the temperature of 580°C and is doped using spin-on-dopant (P609 SOG). Next, photolithography and Reactive Ion Etching (RIE) are used to form poly silicon actuation gate fingers. 7000 A° low temperature silicon dioxide is then deposited using Electron-Beam-Deposition. Single-walled carbon nanotubes with diameter of 1-3 nm were synthesized by chemical vapor deposition (CVD) of methane on the substrate using commercial ferritin (sigma) as catalyst [5]. In order to have access to the poly silicon actuation pads, parts of the oxide over these areas but away from devices are etched using buffered hydrogen fluoride (BHF). Using electron-beam deposition and lift-off, metal contact patterns (Pd/Cr/Au) were created on both ends of the nanotubes to form RF and IF ports and also on the exposed Poly-Si actuation pads to form LO port. At the final step, the areas of silicon oxide under the nanotubes and between metal contacts were etched and devices were dried using critical point drying technique (CPD). The distance between the suspended nanotubes and underneath Poly-Si gates is about 0.5 µm. A Field Emission Scanning Electron Microscopy (FESEM) image of one of the mixer devices is shown in Fig.2.

Fabrication of non-suspended devices is the same as suspended devices except that 1000 A° thermal oxide is grown on the poly silicon pads followed by CNT synthesis. No final etch process or critical point drying was done. The nanotubes in these devices are attached to gate oxide (SiO_2) grown on top of Poly-Si actuation pad.

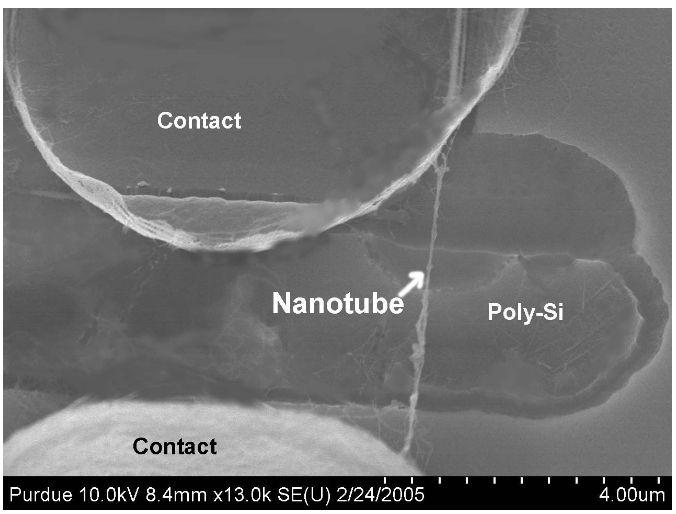

Fig. 2. FESEM pictures of suspended nanotube over a 0.5 µm deep trench.

III. EXPERIMENTAL MEASUREMENT

All samples measured for this experiment have linear IV characteristics with DC resistance around 200 KΩ. In order to investigate the RF mixing performance of these devices, on-wafer probing was used to apply an RF signal $V_{RF}= V_{D\text{-}dc} + V_{ac} \cos(2\pi f_{RF} t)$ to one end of the metallic nanotube (RF port) and LO signal $V_{LO}= V_{G\text{-}dc} + V_{act} \cos(2\pi f_{LO} t)$ to the poly-Si actuation pad (LO port). The output IF signal (other end of the nanotube – IF port) is connected to a spectrum analyzer through a 1.25 MΩ probe. First, open (no nanotube) and through (LO and RF pads connected to output) structures were measured to ensure no artifact IF signal exists either due to input amplifier of the spectrum analyzer or probe non-linear characteristics. Then the mixer device was characterized with constant f_{RF} at 10 MHz while f_{LO} is varied from 10 to 80 MHz. The results show that the nanotube performs as a mixer in this range of frequencies and produces both $f_{RF}+f_{LO}$ and $|f_{RF}-f_{LO}|$ components (Fig. 3). Because of the limited bandwidth of the mixer, the amplitude of the $|f_{RF}-f_{LO}|$ component is higher (~8dB in Fig. 3) than $f_{LO}+f_{RF}$ component and the difference becomes larger at higher frequencies.

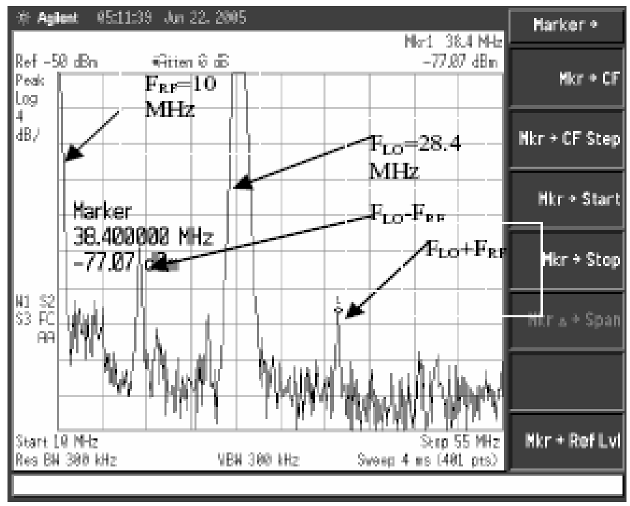

Fig. 3. Both mixed components can be seen. Power is shown after 20 dB attenuation at the probe; V_{RF}= 700 +150 $\cos(2\pi f_{RF} t)$ mV; V_{LO}=707 $\cos(2\pi f_{LO} t)$ mV; fRF=10 MHz; f_{LO}=28.4 MHz, marker at $f_{RF}+f_{LO}$.

The DC components of LO and RF inputs are also varied while IF signal is monitored, but no IF signal dependence on either DC components is observed. So DC voltages were kept constant through the rest of the measurements. On the other hand, the IF output signal strength depends on the AC components of both the RF input and the actuation voltage (LO). Fig.4 shows the output power as a function of input RF signal for two suspended mixer devices (devices a and b) and another device with nanotube attached to the oxide (device c). As the measurement result shows, under identical actuation condition, the suspended nanotube devices (devices a and b) show output powers that are between 8 dB to 13dB higher than the non-suspended device (device c). When the LO signal of the non-suspended device is increased from an amplitude of 700mV to 850mV, the output power and gain of the device becomes comparable with those of the suspended nanotube mixers as shown in Fig. 5.

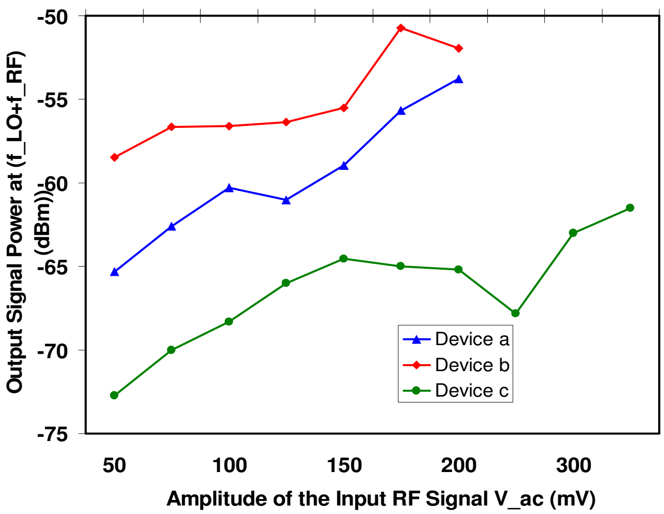

Fig. 4. Output signal for different mixer devices as a function of RF signal, f_{RF}=10 MHz ; f_{LO}=28.4 MHz; Device a,b,c: V_{RF}= 700 +V_{ac} Cos($2\pi f_{RF}t$) (mV),V_{LO}=700 Cos($2\pi f_{LO}t$) (mV). (Devices a and b consist of suspended carbon nanotube while in device c the nanotube is not suspended. All powers have been obtained at $f_{RF}+f_{LO}$ component).

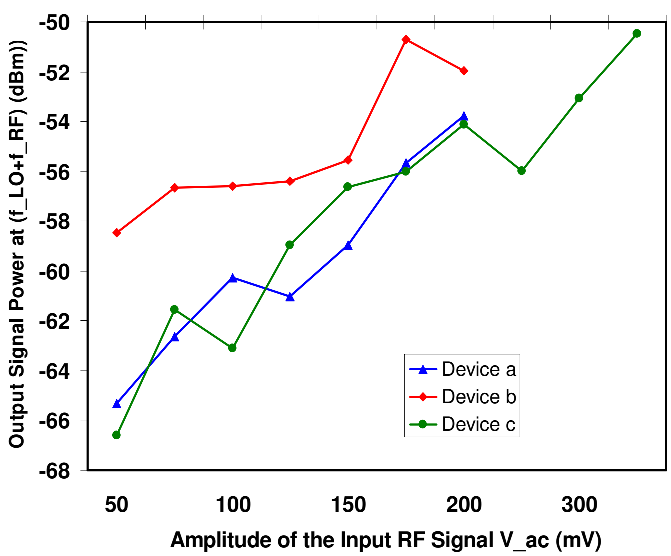

Fig. 5. Output signal for different mixer devices as a function of RF signal, f_{RF}=10 MHz; f_{LO}=28.4 MHz; Devices a,b,c: V_{RF}=700+ V_{ac} Cos($2\pi f_{RF}t$) (mV). Devices a,b: V_{LO}= 700Cos($2\pi f_{LO}t$) (mV), Device c: V_{LO}= 850 Cos($2\pi f_{LO}t$) (mV). (Devices a and b consist of suspended carbon nanotubes while in device c the nanotube is not suspended. All powers have been obtained at $f_{RF}+f_{LO}$ component).

Fig.6 shows the dependence of output IF signal power on LO signal strength. LO signal modulates the conductivity of the carbon nanotube and therefore modulates the signal. Device b which is a suspended nanotube device shows the highest IF output power. It can be seen from the figure that around 6 dB power increment is obtained in device b by increasing the actuation voltage from 420 mV to 840 mV. Mixer voltage convergence-gain as a function of LO is calculated for these devices. As shown in Fig.6 the maximum IF power for device b is around -48dBm. This is attributed to a voltage convergence gain of 5×10^{-3}. If IF signal is measured at $|f_{RF}-f_{LO}|$ slightly higher IF power (-40dBm) and higher convergence gain (4.5×10^{-2}) are achieved. Our experiments show that the gain of the mixer is finely controllable with the actuation signal and that the gain stays generally constant in a wide range of frequencies.

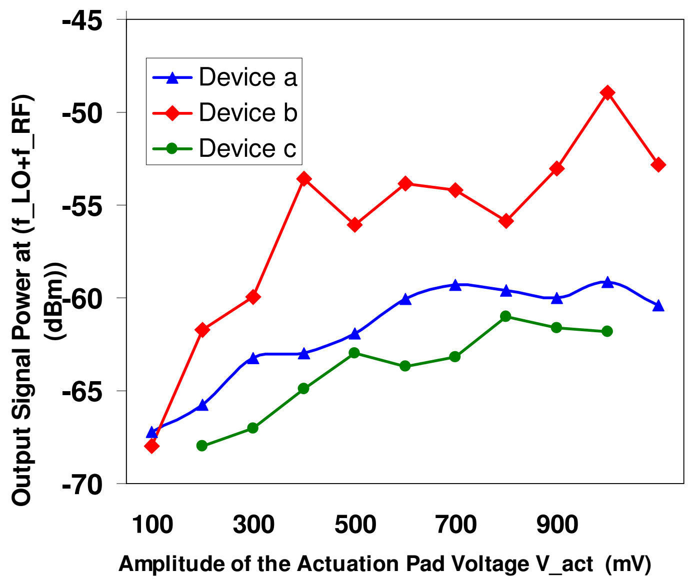

Fig. 6. Output signal for different mixer devices as a function of LO signal, f_{RF}=10 MHz; f_{LO}=28.4 MHz; V_{RF}= 700 +150 Cos($2\pi f_{RF}t$) (mV), V_{LO}=V_{act} Cos($2\pi f_{LO}t$) (mV). (Devices a and b consist of suspended carbon nanotube while in device c the nanotube is not suspended. All powers have been obtained at $f_{RF}+f_{LO}$ component).

IV. DISCUSSION

Various measurements are performed for these mixers to characterize their IF output power and convergence gain. Despite nanotube high impedance, the IF signal is readily detected due to small overlapping parasitic capacitance of the devices. This effect is more pronounced in devices with suspended nanotubes (device a and b) as they have much smaller parasitic capacitance compared to the nanotube device attached to the gate oxide (device c).

The measured output IF signal is proportional to the product of the instantaneous conductance in the nanotube and the input RF current signal entering the nanotube. The nanotube mixer devices reported in [3] are assumed to have an instantaneous conductance that is modulated by mechanical vibration of the nanotube. This was verified by observing high quality factor at the mechanical resonant frequency of the nanotube. On the other hand, in our mixer devices, the mixing performance was observed in a wide range of frequencies for both suspended (device b) and non-suspended (device c) devices as shown in Fig. 7. In this measurement a comparison was made to study the effect of gate-channel capacitance. The result shows that the output IF signal in both devices become identical when non suspended device with higher gate channel capacitance is driven with stronger RF and LO signals compared to suspended device. Nevertheless, the mixing in both cases is due to modulation of the instantaneous conductance with electric field generated by LO signal.

The vibration frequency of the mixer devices reported in [3] was tunable through applying DC actuation voltage (gate voltage). We did not observe any frequency tuning through adjusting DC component of actuation voltage which confirms that the mechanical properties of the nanotube such as stress did not contribute to its mixing performance. As these nanotube mixers are fabricated over a poly-Si gate with an average surface roughness measured at around 16nm, it is expected that the strain in these nanotubes are very small. Therefore, even by applying mechanical vibration, no conductance modulation can be achieved.

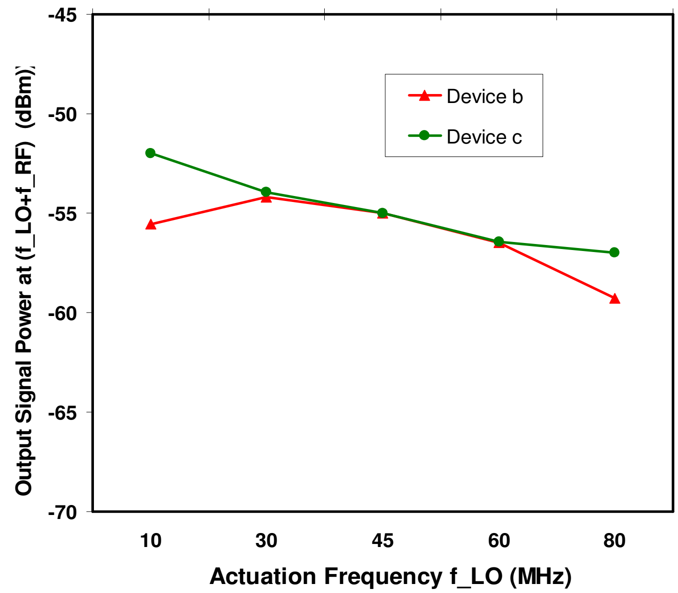

Fig. 7. The output signal for two different mixer devices. In this measurement, Device b : V_{RF}= 700 +150 Cos($2\pi f_{RF}t$) mV and V_{LO}=707Cos($2\pi f_{LO}t$) mV. Device c: V_{RF}= 700 +250 Cos($2\pi f_{RF}t$) mV and V_{LO}=850Cos($2\pi f_{LO}t$) mV ;f_{RF}=10 MHz is kept constant. (Device b consists of suspended carbon nanotube while in device c the nanotube is not suspended. All powers have been obtained at $f_{RF}+f_{LO}$ component).

V. Conclusion

Double clamped single-walled metallic carbon nanotube mixers were fabricated using a combination of poly-Si gate and carbon nanotube synthesis technologies. Performance of these mixers were studied up to 80 MHz. The conductance of the nanotube modulates with the LO actuation voltage and generates two mixing signals. It is shown that suspended devices demonstrate better mixing performance. The fabricated devices take advantage of high thermal budget of Poly-Si with subsequent high temperature CVD growth technique used for carbon nanotube synthesis. This approach also makes it possible to use high resistivity wafers with patterned Poly-Si gate. The structure is suitable for high-frequency measurement as extrinsic parasitic capacitances of the devices are minimized. This is the first report on the performance of carbon nanotubes as a wideband mixer at MHz frequencies.

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