SWNT array resonant gate MOS transistor

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Abstract

We show that thin horizontal arrays of single wall carbon nanotubes (SWNTs) suspended above the channel of silicon MOSFETs can be used as vibrating gate electrodes. This new class of nano-electromechanical system (NEMS) combines the unique mechanical and electronic properties of SWNTs with an integrated silicon-based motion detection. Its electrical response exhibits a clear signature of the mechanical resonance of SWNT arrays (120–150 MHz) showing that these thin horizontal arrays behave as a cohesive, rigid and elastic body membrane with a Young’s modulus in the order of 1–10 GPa and ultra-low mass. The resonant frequency can be tuned by the gate voltage and its dependence is well understood within the continuum mechanics framework.

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(Some figures in this article are in colour only in the electronic version)
Figure 1. (A) Micrograph of a SWNT SG-SiFET. Scale bar: 5 μm. Light blue: ion implanted regions. (B) Schematic cross section of a SWNT SG-SiFET device: Si: silicon wafer (p-type; resistivity: 0.1–0.5 Ω cm). LTO: low temperature silicon dioxide deposited to reduce the parasitic capacitance component from the substrate. n+: ion implanted regions to form source (S) and drain (D) contacts. Al: S and G contacted with aluminum Al lines are 50 Ω designed. CNT: SWNT array deposited by DEP (see details in the text). (C) Electrical circuit of a SWNT SG-FET. C_G is the SWNT gate capacitance per unit length. The SWNT gate forms a thin SWNT membrane on top of the FET channel which can be actuated by applying a voltage difference between the gate and the channel. (D) Detailed view of the SWNT array. Scale bar: 1 μm.

Here we present an alternative way, which is versatile and well adapted to integrate extremely thin SWNT arrays to CMOS transistors and demonstrate the first resonant SWNT array suspended gate FET, fully compatible with any bulk silicon CMOS technology. The SWNT suspended gate FET device (SWNT SG-SiFET) combines the virtues of SWNT suspended arrays (stiff and light material used as the vibrating gate of a silicon field effect transistor (SiFET)), with integrated transistor detection. The high frequency vibration of the SWNT array modulates the charge density in the FET channel and the output signal of the resonator is the drain current. The electrical response shows the signature of the mechanical resonance of SWNT arrays (120–150 MHz) demonstrating that these extremely thin horizontal arrays behave as a cohesive, rigid and elastic body membrane. The resonant frequency can be tuned by the gate voltage and its dependence is well understood within the continuum mechanics framework.

Figure 1 shows a micrograph of a SWNT SG-SiFET and its schematic cross section. The fabrication details of the SiFET are described elsewhere [23]. Suspended SWNT gates centered on the FET channel were fabricated as follows: first, chromium/platinum Cr/Pt (5 nm/60 nm) lines were patterned perpendicular to the FET channel (see figures 1(A) and (B)). These electrodes were used to deposit a dense array of SWNTs, mostly centered on top of the SiFET channel, by a dielectrophoresis (DEP) process. The DEP step is described in detail elsewhere [17]. The SWNTs used have a small diameter dispersion centered on 1.2 nm. The SWNTs used were synthesized by laser ablation, first purified and then dispersed at low concentration in N-methylpyrrolidone using moderate sonication, resulting in a highly stable dispersion comprising mostly individual nanotubes. A droplet of this dispersion is deposited on the wafer. An ac electric field is applied between the access electrodes of the future gate contacts. This electric field drives the deposition of the nanotubes. After dielectrophoresis deposition of the SWNTs, the droplet is rinsed with acetone in order to remove the N-methylpyrrolidone, letting the nanotubes be localized between the electrodes. To give a precise geometry to the SWNT gate, an e-beam lithography step followed by reactive ion etching (O2/SF6) was realized. Finally Ti/Au (10 nm/50 nm) electrodes were patterned by e-beam lithography and lift-off technique to doubly clamp and electrically contact the SWNT gate to metallic lines. The SWNT gate was suspended by etching the sacrificial layer in BHF. This step was done only in the central region, through an e-beam patterned PMMA mask, to avoid damaging the Al electrodes of the SiFET. The e-beam mask was stripped in acetone followed by critical point drying. The final air-gap of the fabricated device is ~100 nm, with a residual oxide thickness of ~35 nm.

Since the DEP technique favors the deposition of metallic nanotubes, the resulting suspended SWNT arrays obtained show a metallic behavior and can be suitably used as suspended gates. They are actuated by applying a $V_G$ voltage on one of the metallic clamping electrodes. The electrostatic force on the SWNTs membrane for $V_G = V^{DC} + v_G \cos \omega t$ and $V^{DC}_G \gg v_G$ can be well approximated by

$$F_d \simeq \frac{1}{2} C'_G V^{DC}_G \left[ V^{DC}_G + 2 v_G \cos \omega t \right]$$

(1)
where $C'_G$ is the first derivative of the gate capacitance per unit length with respect to the gap separation and $V^{DC}_G = V^{DC}_G - V_{Gint}$ and $V_{Gint}$ the mean value of the channel potential\(^3\). The first term of (1) corresponds to the DC component that elastically deforms the SWNT membrane and sets its mechanical tension and the second drives its motion at frequency $\omega$. The SWNT membrane motion induced by the AC component of $V_G$ modulates the capacitance $\delta C_G$ which in turn modulates the charge in the channel. The conductance channel change $\delta G$ can be written as

$$\delta G \simeq \frac{dG}{dV_G} \left( V^{\cos}(\omega t) + \frac{\delta C_G(\omega)}{C_G}(V^{DC}_G) \right).$$

(2)

To detect this conductance change at $\omega$ we use the device as a mixer: we apply an AC voltage $V^{\cos}(\omega t - \phi)$ between the source and drain\(^4\) and an AC gate voltage $V_G \cos(\omega t)$ chopped by a switch operated at audio frequency $f_A$ (typically 133 Hz, see the setup depicted in figure 2).

The source–drain current has a component $I^{LI}$ at $f_A$ which is detected by a lock-in amplifier:

$$I^{LI} = \frac{\sqrt{2}}{\pi} \frac{dG}{dV_G} \left( \frac{\delta C_G}{C_G} V^{DC}_G + V_G \right) V_{DS}. $$

(3)

The first term contains the mechanical response of the SWNT array. For small motional amplitudes, the membrane can be treated as a simple harmonic resonator [24] with effective mass $M = \xi \rho WLH$, $\xi \cong 1.448$ 58 and $\rho$, $W$, $L$ and $H$ are the mass density, width, length and thickness of the membrane respectively. The change in capacitance $\delta C_G(\omega)$ can be well approximated by $\delta C_G(\omega) \cong C'_G/2\pi$ where $\delta y(\omega)$ is the displacement of the mid-point of the resonator and can be obtained from the effective harmonic oscillator equation (see equation (6) below):

$$\delta y(\omega) = \frac{C'_G V^{DC}_G V_G}{M} \left[ \text{Re} Y(\omega) \cos \omega t - \text{Im} Y(\omega) \sin \omega t \right]$$

(4)

where $Y = (\omega^2 - \omega^2 + j\omega \delta \omega/Q)^{-1}$ is the response function of a harmonic oscillator with resonant frequency $\omega_0$ and quality factor $Q$, driven at frequency $\omega$. Then the lock-in current reads:

$$I^{LI} = I_B \left( \text{Re} Y(\omega) \cos \phi + \text{Im} Y(\omega) \sin \phi \right)$$

(5)

where $I_B = \sqrt{2}/\pi (dG/dV_G) V_{DS} V_G$, $A = \frac{C'_G V_G}{M}$ and the phase difference between the RF signal on the gate and source electrodes is $\phi$. Using this expression, data can be fitted and the gate voltage dependence of the resonant frequency $f_0(V^{DC}_G) = \omega_0/2\pi$ and the quality factor $Q$ can be estimated.

Figure 3 shows the mixing current $I^{LI}$ measured on device #1 ($L = 800$ nm) as a function of the excitation frequency for five different values of $V^{DC}_G$ and their best fit using expression (5) and $I_B$, $A$, $\omega_0$, $Q$ and $\phi$ as fitting parameters. Data were taken in the linear regime (low AC amplitudes) under vacuum (10\(^{-5}\) mbar) and at room temperature. The size of the resonance feature increases with increasing DC gate voltage making evident the increase of the SWNT membrane deflection amplitude. The position in frequency of the resonance (in the 150–160 MHz range) moves downward with the increase of the gate voltage showing a counter-intuitive effective softening of the SWNT membrane spring constant. Thanks to the array configuration, the output signal level of our SWNT array resonator is approximately one order of magnitude higher than the one reported in [4] and [25], using a hybrid SWNT/SiFET configuration for building MEM oscillators. Moreover, the output signal level of the SWNT array SG-SiFET can be further increased by operating the transistor at higher DC $V_{DS}$ (saturation mode). In this work, we mainly focus on the electromechanical behavior of the SWNT array and on demonstrating the basic operating behavior of such a device.

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\(^3\) Supplementary information available at stacks.iop.org/Nano/22/055204/mmedia describes the procedure used to estimate its value.

\(^4\) The phase difference between the gate and source electrode depends on the frequency of the rf signals, on the (gate dependent) conductance of the nanotube, and on its derivative. Moreover, the lock-in detected phase does not contain any information about $\phi$.  

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Figure 2. Diagram of the measurement setup. BS: beam splitter. SW: GaAs TTL switch. The device is operated as a mixer. A single rf generator provides two AC voltage signals: one amplitude modulated by SW (operated at $f_A$) and applied to the gate electrode to drive the suspended nanotube array and a second applied to the S electrode ($v_{DS}$). A DC gate voltage is added via a bias-T (indicated by the ‘T’). Its role is two-fold: modify the operating point of the FET and set the mechanical tension of the SWNT array. At the drain electrode D, the mixing current has a spectral component at $f_A$ which is measured with a lock-in amplifier.

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Figure 3. Mixing current $I^{LI}$ as a function of the driving frequency for different values of $V^{DC}_G$ for device #1. AC amplitudes are: $v_G = -29$ dB m and $v_{DS} = -24$ dB m. Red curves: best fit using equation (5).
second term on the right-hand side of (6) comes from the nonlinear dependence of the gate capacitance $C_G$ with the vertical coordinate. This term renormalizes the spring constant and produces a softening of the resonator. Then the resonant frequency of the SWNT array can be written as follows (see SI available at stacks.iop.org/Nano/22/055204/mmedia for details)

$$f_0(V_G^{DC}) = \frac{1}{2\pi} \sqrt{\frac{K - C''_G(V_G^{DC})^2}{M}}$$

$$= \left\{ f_1^2(1 + \alpha \tilde{T}_0) - \beta(V_G^{DC})^2 + f_2^2 \alpha \int_0^1 \left( \frac{dy_0}{dx} \right)^2 dx 
+ f_1^2 \kappa \left( \int_0^1 \frac{d^2y_0}{dx^2} u_1(x) dx \right)^2 \right\}^{1/2} \quad (7)$$

where $f_1 \approx 1.03 \frac{H}{\sqrt{m \omega}}$ corresponds to the fundamental resonant frequency of a doubly clamped beam, $\alpha \approx 0.1475$, $T_0 = \tilde{T}_0(EWH^2/2L^2)$ is the mechanical residual tension when $V_G^{DC} = 0$, $\beta = \epsilon_0/(4\pi^2 \rho H_0^2)$ and $\kappa \approx 0.0166$. The third and fourth terms in (7) are the DC gate voltage dependent hardening of the effective spring constant due to the elastic deformation of the beam. Numerical simulations show that the sum of these two terms can be written as $\lambda(E, \tilde{T}_0)(V_G^{DC})^2$. As a result, the proposed model quantitatively fits our data if $\beta \gg \lambda(E, \tilde{T}_0)$.

AFM characterization of our devices shows that the thickness of the SWNT array is inhomogeneous. The mean value of the SWNT membrane thickness is about $(20 \pm 10)$ nm for both devices. The imperfect packing and alignment of SWNTs, which produces the mechanical cohesiveness of the SWNT membrane, makes its density unknown. However, from the data at low gate voltages one could estimate the value of $\beta$ and use its definition to obtain an effective density $\rho_{eff}$. This yields: $(700 \pm 400)$ kg m$^{-3}$ for device #1 and $(400 \pm 200)$ kg m$^{-3}$ for device #2. Using this estimation and $E$ and $T_0$ as fitting parameters one could obtain the results depicted in figure 4. For comparison we also show the best result considering $T_0 = 0$ (black dash curve) and using only $E$ as a fitting parameter (120 GPa and 610 GPa for device #1 and #2 respectively). The red curves correspond to the best fit: $E = (3 \pm 1.5)$ GPa, $T_0 = (2 \pm 0.1) \mu$N for device #1 and $E = (10 \pm 5)$ GPa, $T_0 = (1 \pm 0.1) \mu$N for device #2. The gray region represents the uncertainty on the thickness $H$ for device #1 and the sensitivity to the value of $E$ for device #2. The quantitative agreement makes evident the finite value of an in-built mechanical tension. This mechanical tension can probably be attributed to the suspension step of the SWNT membranes. The impact of the dielectrophoresis field on $T_0$ will be further investigated. The value obtained for the Young’s modulus is better than the one reported for bucky paper [26] 2.3 GPa and comparable to the one reported for highly aligned SWNTs [15] or slightly smaller [16], supporting that our SWNT arrays of a thickness as small as 15 nm behave as highly ordered wafers.

The quality factor obtained from fitting $I^{11}(\omega)$ is 35–55 for both devices. This value is comparable to the one reported by Hayamiizu et al [16] for highly aligned SWNT thick cantilevers ($H \cong 250$ nm) and suspended graphene [27].
but lower than the one reported for single arc discharged SWNTs [9]. One possible explanation is related to the energy loss due to loosely linked SWNTs inside the membrane. This value could be improved by suppressing the sliding among SWNTs via cross-linking between them, as suggested in [28].

In conclusion, SWNT suspended membrane gates were successfully integrated to MOS transistors and operated at a high frequency for the first time. These extremely thin membranes behave as a cohesive, rigid and elastic body. In particular, the resonant frequency of SWNT SG-SiFETs is tuned by the DC gate voltage and its dependence can be well described within the continuum mechanics framework. The mechanical properties of SWNT arrays are comparable to those observed in closely packed and aligned SWNT wafers [15]. The quality factor observed makes SWNT membranes more suitable for high frequency mechanical switching devices because of the quick damping of vibration. This work shows promise to realize devices with practical applications using CNT, for example in bio-sensing and RF electronics.

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