Nanotechnology 24 (2013) 435203 (10pp)

High frequency top-down junction-less silicon nanowire resonators

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Received 22 May 2013, in final form 12 September 2013 Published 9 October 2013 Online at stacks.iop.org/Nano/24/435203

Abstract

We report here the first realization of top-down silicon nanowires (SiNW) transduced by both junction-less field-effect transistor (FET) and the piezoresistive (PZR) effect. The suspended SiNWs are among the smallest top-down SiNWs reported to date, featuring widths down to \sim 20 nm. This has been achieved thanks to a 200 mm-wafer-scale, VLSI process fully amenable to monolithic CMOS co-integration. Thanks to the very small dimensions, the conductance of the silicon nanowire can be controlled by a nearby electrostatic gate. Both the junction-less FET and the previously demonstrated PZR transduction have been performed with the same SiNW. These self-transducing schemes have shown similar signal-to-background ratios, and the PZR transduction has exhibited a relatively higher output signal. Allan deviation (σ_A) of the same SiNW has been measured with both schemes, and we obtain $\sigma_A \sim 20$ ppm for the FET detection and $\sigma_A \sim 3$ ppm for the PZR detection at room temperature and low pressure. Orders of magnitude improvements are expected from tighter electrostatic control via changes in geometry and doping level, as well as from CMOS integration. The compact, simple topology of these elementary SiNW resonators opens up new paths towards ultra-dense arrays for gas and mass sensing, time keeping or logic switching systems on the SiNW-CMOS platform.

S Online supplementary data available from stacks.iop.org/Nano/24/435203/mmedia

(Some figures may appear in colour only in the online journal)

1. Introduction

During the last decade, nanoelectromechanical systems (NEMS) have shown great promise for both fundamental science and applications, providing new tools for studying quantum physics [1, 2] including electromechanics and optomechanics [3]. Technological applications of NEMS are also emerging: these include integrated frequency clocks [4], logic switches [5], mixer filters [6], ultra-sensitive force detectors [7] and mass sensors [8]—in this case the measurement consists of tracking the resonance frequency shift caused by elements landing on the surface. The key to

real-world implementation though is a scalable, integrated, low-power transduction scheme, associated with a fabrication process allowing for individually addressable devices in ultralarge, ultra-dense arrays. Essential bricks of the puzzle have started to fall into place in recent years: VLSI-compatible transduction schemes have been proposed [9, 10] for individual devices, and their implementation in real systems has been demonstrated for gas sensing [11] as well as for realtime single-molecule mass spectrometry [12]. Nevertheless, these NEMS include a fairly large number of electrical contacts per device, making their individual addressing



Figure 1. Suspended junction-less Si nanowires with gate electrodes, in lateral field-effect transistor (FET) configuration. (a) 3D-schematic of the suspended SiNW showing layers: red for oxide, grey for silicon and yellow for metal. Lengths vary from 800 nm to 3 μ m, widths from to 80 to 20 nm, gaps from 250 to 80 nm. Typical cross-sections ranged from 20 × 20 nm² to 30 × 40 nm² depending on the use of oxidation steps for rounding the nanowire shape. (b) Scanning electron microscope (SEM) image of a SiNW resonator with two actuation electrodes (G1 & G2). (c) Close-up of the SiNW—the white dotted line shows the undercut of the released buried oxide. (d) Transmission electron microscope (TEM) cross-section of a typical nanowire prepared by focused ion beam (FIB)—the silicon cross-section has dimensions of 32 nm × 25 nm.

complex when in arrays. Even though a major step forward was accomplished with the first realization of LSI NEMS arrays in collective addressing fashion [13], a transduction and readout scheme allowing simple, extremely compact and smart NEMS pixels is yet to be developed. Recently an elegant two-source, piezoresistive self-transducing scheme has been used with a carbon nanotube (CNT) and has shown sufficient signal-to-noise ratio (SNR) for sensitive detection [14]. A one-source field-effect transduction of CNTs has shown enough gain to demonstrate a few Dalton to a few tens of Dalton mass resolution [8]. The bottom-up fabrication process of the two latter cases has not allowed for scalability so far. On the other hand, scalable nanomechanical transductions have been proposed recently [15, 16] where a fin field-effect transistor and a first type of junction-less field effect are embedded into the NEMS. However, the top-down processes used in these studies to obtain the necessary effects require localized doping with advanced lithography and additional mask levels.

In this paper, we introduce a low-power, scalable, top-down fabrication process with simple full sheet doping (i.e. one single dopant concentration for the suspended SiNW and the control gate), and minimum number of mask levels. We demonstrate the simple implementation of a junction-less field-effect transduction (only enabled by the minimum feature size achieved, below 30 nm) as well as a piezoresistive (PZR) self-transducing scheme, on the same device. Two simple models are also introduced to qualitatively explain the electrical signals obtained with the two detection schemes when the nanowire is vibrating. Both detection schemes are carefully compared: electromechanical and frequency stabilities of the same SiNW have been measured with both schemes at room temperature and low pressure.

This comprehensive demonstration paves the way towards integrated low-cost, low-power, ultra-dense, ultralarge arrays of highly sensitive NEMS for various real-world applications.

2. Device operation and fabrication process

We report here a self-transducing NEMS device based on a suspended silicon nanowire resonator (SiNW), see figure 1(a). Each device comprises a doubly clamped beam electrically connected on both ends, as well as two lateral electrodes (for both actuation and detection). The mechanical motion is detected by monitoring the output current produced by conductance modulation of the SiNW. This modulation is obtained via two different principles: tension-induced piezoresistivity and junction-less field effect where the SiNW is itself a monolithic suspended transistor. Both principles are made possible thanks to the intrinsic properties of silicon, ubiquitous in the standard microelectronics industry and its associated tools. These tools allow for NEMS with widths from 20 to 40 nm and lengths on the order of a few

microns, with measured resonances from 30 to 150 MHz (see figures 1(b)-(d)).

The fabrication process is based on CMOS-compatible techniques in order to facilitate future co-integration with electronic circuitry on the same substrate. The initial wafer is a silicon-on-insulator (SOI) wafer, which facilitates the release of the mechanical structure. First, the Si film of the SOI wafer is homogeneously p-type implanted with boron ($N_a =$ 10^{19} cm⁻³) and then hybrid e-beam/DUV (deep ultra-violet) lithography is used for the patterning of both nanowires and pads. Next, etching of the devices and release of the structures (with hydrogen fluoride) are performed. In order to passivate the SiNW a thermal oxide of about 10 nm is grown around the whole NW. Before the metallization of the contact pads, a layer of poly-Si is deposited to protect the release devices. The poly-Si is etched and AlSi is deposited to make the pads. The process flow is similar to the CMOS process presented elsewhere [17]. The final step is a second release of the resonators with etching of the poly-Si. The initial Si film is reduced down to 30 nm by thermal oxidation, while the thermal oxide surrounds the structure. The nanowire crystal is oriented $\langle 110 \rangle$. This orientation is chosen to enhance the piezoresistive effect (see for example [18]). It should be noted that both nanowire and actuation electrodes are doped at the same initial level ($N_a = 10^{19} \text{ cm}^{-3}$) with boron. In both cases the effective dopant concentrations in the SiNWs have been found to be lower than the full sheet doping level. From resistance measurements the effective doping has been found to vary with the NW width, with lower values for thinner NWs. The doping concentration is 3.8×10^{17} cm⁻³ for thin SiNWs (w = 35 nm), while for thicker nanowires (w = 80 nm) the extracted effective dopant concentration is $\sim 10^{18}$ cm⁻³. This phenomenon, caused by both a depletion effect and a dopant deactivation, is well described in several studies [19, 20] (see supplementary information available at stacks. iop.org/Nano/24/435203/mmedia).

SiNWs with various geometries have been tested, but in the following, only results obtained with two different devices are presented (see supplementary information for results with other devices available at stacks.iop.org/Nano/24/ 435203/mmedia). The first one termed hereafter N67MHz is 2 μ m-long, 35 nm-wide. The gap between electrodes and the nanowire is 152 nm. The second suspended SiNW termed hereafter N120MHz is 1.5 μ m-long, 35 nm-wide. The gap between electrodes and the nanowire is 82 nm. The thickness is 30 nm for both SiNWs. The frequency response of other devices are presented in supplementary information (available at stacks.iop.org/Nano/24/435203/mmedia).

The mechanical motion of such SiNWs modulates their electrical resistance through the piezoresistive effect. The extraction of SiNW PZR gauge factors has been discussed elsewhere, for example in [20]. Gauge factors G between 80 and 240—depending on the doping concentrations and surface states, see supplementary information (available at stacks. iop.org/Nano/24/435203/mmedia)—have been extracted for similar SiNWs. Moreover, static field-effect measurements will be presented as evidence of conductance modulation by electrostatic control [21]. This effect was first presented

for a suspended vibrating body by Bartsch *et al* [16]. The possibility of controlling the current inside the nanowire with two uncorrelated approaches allowed us to perform resonance detection with two different self-transducing techniques.

2.1. Piezoresistive (PZR) effect

The PZR effect consists in the modulation of the resistance by application of mechanical strain on the device—that is the case for the PZR NW [14]. In fact, mechanical strain changes both the cross-section of the nanowire and the band curvatures resulting in a different conductivity inside the SiNW [20]. For the semiconductor nanowires, the contribution of the resistivity variation dominates over that due to the geometric change, and the relative resistance variation can be written as

$$\frac{\Delta R}{R_0} = \frac{\Delta \rho}{\rho_0} = \varepsilon_1 G \tag{1}$$

where ε_1 is the longitudinal strain and G the gauge factor.

Gauge factors extracted from our four-point bending tests are close to 240 as observed previously [20] for the two main devices tested in the work (N67MHz & N120MHz)—the measurement method is detailed in [20].

The second-order PZR effect for resonating doubly clamped nanowires can be used for efficient transduction: the axial strain is then proportional to the square of the nanowire displacement (the first-order stress field due to flexion is symmetric in a cross-section, and hence the overall first-order resistance is cancelled out) [14]:

$$\frac{\Delta R}{R} = G \frac{\pi^2}{4} \left(\frac{a}{L}\right)^2. \tag{2}$$

L is the nanowire length and *a* is the nanowire amplitude at the centre: $a(\omega) = z_1(\omega)\phi(\frac{L}{2})$ ($z_1(\omega)$) is the Fourier transform of the temporal part and $\phi(L/2)$ is the modal displacement).

The output current I_{ds} is measured when applying a drain-source voltage $V_{DS}(\omega)$ and can be expressed as follows:

$$I_{\rm DS}(\omega) = \frac{V_{\rm DS}(\omega)}{R_{\rm DS}(\omega)} = \frac{V_{\rm DS}(\omega)}{R_0} \left(1 - \frac{\Delta R}{R_0}\right)$$

= $I_{\rm DS0}(\omega) + I_{\rm ds}(\omega)$
 $I_{\rm ds}(\omega) = \frac{V_{\rm DS}(\omega)}{R_0} G \frac{\pi^2}{4} \left(\frac{a(\omega)}{L}\right)^2.$ (3)

The dynamic output current $I_{ds}(\omega)$ can be expressed with respect to the drain voltage $V_{ds} = V_{Bias} \cos((\omega - \Delta \omega)t)$ and the actuation signal applied on the gate $V_{Actuation} = V_G + V_{AC} \cos(\omega t)$ in a down-mixing scheme (the SiNW acts like a non-linear mixer between actuation and bias). The NW's transverse displacement is proportional to the square of the actuation voltage and the drain current scales like V_{Bias} and V_{AC}^2 . The nanowire is assumed to follow the Euler–Bernoulli equation. This equation is reduced to its normalized lumped expansion on the first mode through the Galerkin method for defining the nanowire amplitude at the centre $a(\omega)$ (see for example [22]). Substituting the expression of $a(\omega)$ in (3), the output current close to the resonance frequency is

$$I_{\rm ds}(\omega_0) = G \frac{V_{\rm Bias}}{R_0} \frac{\pi^2}{4L^2} \frac{Q^2}{m^2 \omega_0^4} \frac{(C_{\rm n} \varepsilon_0)^2 L^2 t^2 V_{\rm G}^2 V_{\rm AC}^2}{g^4}$$
$$I_{\rm ds}(\omega_0) \propto V_{\rm Bias} V_{\rm AC}^2, \tag{4}$$

where g and t are the electrostatic gap and the nanowire thickness respectively. C_n , ε_0 are the fringe effect corrective factor (see their computation in supplementary information available at stacks.iop.org/Nano/24/435203/mmedia), and the vacuum permittivity respectively. Q is the quality factor, m the effective nanowire mass ($m = 0.75 \rho Lwt$) and R_0 the nanowire resistance at zero strain. The effective mass is calculated from the normalization condition in the Galerkin projection: m = $\frac{L}{\varphi(L/2)\int_0^l \varphi(x)dx}$. From equation (4) it is noticed that the output is proportional to the bias, while it varies quadratically with the AC-actuation V_{AC} : with f being the actuation (excitation) frequency, the drain current I_{ds} varies at 2f. It should be noted here that the gauge factor can also be roughly estimated with equation (4), by measuring the current at resonance if the factor C_n is carefully computed (see PZR measurements below).

3. Field-effect transduction

The junction-less field-effect transistor (FET) configuration allows the modulation of the SiNW resistance by electrostatic control. The SiNW constitutes a simple resistance controlled by an actuation electrode doped at the same level as the nanowire. The SiNWs are surrounded by a SiO_2 layer of 10 nm, with an air gap of some tens of nanometres between the nanowire and the actuation electrode. Unlike transistors normally off-state at zero-gate voltage (accumulation mode transistors, typical junction-less transistors), our nanowire is at the on-state for $V_{\rm G} = 0$ and the nanowire remains neutral. The application of a DC voltage between the gate and actuation electrode modulates the number of free carriers in the nanowire resulting in a variation of the resistance. For p-type nanowires, increasing the gate voltage (for $V_{\rm G}$ > 0) will gradually deplete the device thus reducing the current. The depletion mechanism for the device N120MHz is illustrated in supplementary information (available at stacks. iop.org/Nano/24/435203/mmedia) with COMSOL simulation based on the finite element method. The nanowire mainly works in a bulk conduction regime. The computation of the depletion width can however be inspired by the method used in accumulation mode transistors [23]. Based on the assumption of abrupt channel depletion, the width d of the depleted region can be calculated from the following equation [24]:

$$d(x) = \frac{-\varepsilon_{s}}{C_{i}} + \sqrt{\left(\frac{\varepsilon_{s}}{C_{i}}\right)^{2} + \frac{2\varepsilon_{s}}{eN_{a}}\left(V_{G} - V_{FB} - V_{DS}(x)\right)}, (5)$$

where ε_s is the permittivity of silicon, N_a is the dopant concentration, *e* is the electron charge (1.6×10^{-19} C), and *C*_i is the insulator capacitance including the oxide surrounding

the nanowire and the air gap between the wire and the gate electrode. $V_{\rm G}$, $V_{\rm FB}$ and $V_{\rm DS}(x)$ are the gate voltage, the flat-band voltage and the voltage along the channel respectively ($V_{\rm DS}$ is equal to $V_{\rm Bias}$ in AC mode). The flat-band voltage depends on both the difference in work function between the gate and channel and the charge trap density at the silicon/oxide interface and in the oxide, $Q_{\rm ss}$ [24].

The resistance per unity of length of the nanowire is then

$$dR = \frac{\rho(T, N_a)dx}{t(w - 2d(x))}.$$
(6)

Under the assumption of a gradual channel, the differential source/drain current can be deduced from the resistance:

C

$$dI_{\rm DS} = \frac{dV_{\rm DS}}{dR}.$$
(7)

The bulk current through the nanowire is obtained by integration of equation (7) along the channel. After a straightforward mathematical development an analytical expression of drain current, transconductance—in the linear regime—can also be found:

$$I_{\rm DS}(V_{\rm G}, V_{\rm DS}) = \frac{2t}{\rho L} \left[\left(\frac{w}{2} - \frac{C_{\rm i}}{eN_{\rm a}} (V_{\rm G} - V_{\rm FB}) \right) V_{\rm DS} + \frac{C_{\rm i}}{eN_{\rm a}} \frac{V_{\rm DS}^2}{2} \right]$$

$$g_{\rm m} = \frac{\partial I_{\rm DS}}{\partial V_{\rm G}} = \frac{-2t}{\rho L} \frac{C_{\rm i}}{eN_{\rm a}} V_{\rm DS}.$$
(8)

This equation is a helpful estimation of the drain current to understand the high frequency electromechanical response. The bulk current should nevertheless saturate at the flat-band voltage and the further drain current increase at higher gate voltages may be due to the accumulation current. Notice that a more comprehensive model of a similar device including the accumulation regime has been proposed in [25].

Field-effect measurements have been performed in the static regime with a manual probe on the suspended nanowires N67MHz (with a dopant concentration of $3.8 \times 10^{17} \text{ cm}^{-3}$). Typical experimental characteristics $I_{\text{DS}}(V_{\text{G}})$ for the N67MHz and N120MHz are plotted in figures 2(a) and (b) respectively.

Theoretical drain currents obtained from equation (8)are also plotted in figure 2 for a crude validation of the analytical model. The only parameters necessary for the drain current calculation are the surface charge density and the doping level. For the two suspended SiNWs we consider a charge density $Q_{\rm ss}$ close to 2.5 imes 10¹¹ cm⁻² which corresponds to the value found for a similar fabrication process [20]. For the device N67MHz the doping level is set at 4×10^{17} cm⁻³ which is the experimental value. For the N120MHz the dopant concentration is set at 6×10^{17} cm⁻³, slightly larger than the experimental value for a good fit with measurements. The air gap capacitance C_i and the hole mobility μ_p have to be known for a reasonable fit of the experimental data. C_i computation is based on the simple parallel plate capacitance model but includes the fringe effect: the parallel plate capacitance value is multiplied by a magnification factor C_n that is evaluated at 1.95 and 1.5



Figure 2. SiNW field-effect transistor characteristics. (a) $I_{DS}(V_G)$ characteristics for different drain voltages for the nanowire N67MHz—log plot. Increasing the gate voltage leads to depletion of the conduction channel and hence to a decrease of the passing current. (b) $I_{DS}(V_G)$ characteristics for different drain voltage V_{DS} for the suspended SiNW N120MHz—log plot. Here the gate voltage is set to reach a stronger depletion. The current is divided by a thousand when increasing the gate voltage from 0 to 25 V. Above 25 V, a leakage current of a few nA seems to appear. (c) Transconductance g_m according to V_G for the device N120MHz: the nanowires used here have a similar structure to MOSFETs with the actuation electrode corresponding to the gate, the oxide corresponding to the dielectric and the nanowire to the transistor channel.

for the devices N67MHZ and N120MHz, respectively. μ_p is computed around 200 cm² V⁻¹ s⁻¹ close to the mobility in bulk silicon (see supplementary information available at stacks.iop.org/Nano/24/435203/mmedia). Equation (8) gives fairly good trends and right orders of magnitude of the drain current for all data sets. A rough valuation of the flat-band voltages $V_{\rm FB} = -qQ_{\rm ss}/C_i$ with $q = 1.6 \times 10^{-19}$ C (neglecting the work-function difference) leads to $V_{\rm FB} = -3.5$ V and -2.5 V for the devices N67MHz and N120MHz respectively. The depletion voltage (or threshold voltage) is around 23 V for the device N120MHz at low $V_{\rm DS} = -1.5$ V. For the second device N67MHz, the depletion voltage is close to 14 V at low $V_{\rm DS} = -1.5$ V. The threshold extraction is based on the ELR (extrapolation in the linear region) method.

In many cases the model fits well the experimental curves for low $V_{\rm G}$ and low $V_{\rm DS}$ since it overestimates the experimental drain current for larger $V_{\rm G}$. A reduction of the hole mobility (due to perpendicular electric field) could explain the discrepancy at large $V_{\rm G}$ even if there is less carrier mobility degradation in comparison to a transistor with a surface conduction mechanism [26]. The divergence at large $V_{\rm G}$ is further discussed when considering

the transconductance. Additional current variation may be caused by the PZR mechanism since the SiNW undergoes stress when in motion. However, the static displacement does not overcome 1 nm for the voltages used here. The induced axial stress remains close to zero averaged over its nanowire cross-section and hence the PZR contribution to the drain current remains negligible.

A leakage current seems to appear when the nanowire is close to complete depletion. The origin of this leakage current is not well understood yet. Two assumptions can nevertheless be made. At strong $V_{\rm G}$, a field emission between the corners of the drain/source pads and the corners of the gate pad might be triggered. No mechanical deflection due to residual stress had been observed before applying the large gate voltage. However, due to fabrication imperfections, the nanowire section is not perfectly symmetric. Electrical field could cause some spurious displacement (out of the wafer plane for instance), degrading hence the electrostatic control of the gate. In the electromechanical measurements the background current is removed using a heterodyning technique as described in the next section. The theoretical and experimental transconductance $g_{\rm m}$ of the device N120MHz are close to 3×10^{-7} S and 10^{-7} S for $V_{\rm DS} = -4.5$ V and -1.5 V respectively (see figure 2(c)). These values are similar to the values obtained with the suspended Fin-FET transistors [15]. $g_{\rm m}$ is roughly multiplied by three when the drain voltage increases from 1.5 to 4.5 V. $g_{\rm m}$ is however bias-dependent in particular for large $V_{\rm DS}$ (red line in figure 2(c)). The shapes of $g_{\rm m}$ cannot actually be understood with our simple model, which does not consider the mobility variation and the series resistance [27]. Moreover the channel, the drain and the source of our device are uniformly doped (same 10^{19} cm⁻³ in our case). In this case, it has been reported that the channel length and the series resistance become highly bias-dependent close to or above the flat-band voltage [28].

When performing resonance measurements, the suspended SiNW is actuated by a dc and an ac signal applied to the gate. The dc voltage will deplete the NW in a constant way, while the ac signal will deplete the NW in a dynamic mode. The effective gate voltage depends on the capacitance bridge formed by the air capacitance that is modulated by the beam displacement and the oxide capacitance around the NW. Knowing the transconductance g_m , the current variation caused by nanowire oscillations can be expressed according to actuation and bias voltages to obtain a similar expression as in (4). Keeping the same notation for actuation and bias voltages, close to the resonance frequency the output current can be expressed as

$$I_{\rm ds}(\omega_0) = g_{\rm m} \delta V_{\rm G}(\omega_0) \approx g_{\rm m} V_{\rm G} \frac{\delta C(\omega_0)}{C_{\rm gap}} = g_{\rm m} V_{\rm G} \frac{a(\omega_0)}{g}$$

$$I_{\rm ds}(\omega_0) = g_{\rm m} V_{\rm G} \frac{4}{3} \frac{(C_{\rm n} \varepsilon_0 Lt) V_{\rm G} V_{\rm AC}}{g^3} \frac{Q}{m \omega_0^2}$$

$$I_{\rm ds}(\omega) \propto V_{\rm Bias} V_{\rm AC},$$
(9)

where C_{gap} is the air gap capacitance. The oxide capacitance is neglected as it is small and in series. The other parameters have been defined elsewhere in the text.

Equation (9) shows how the nanowire resistance is modulated by the field effect, which is a first-order phenomenon as opposed to the PZR transduction described above. With *f* being the bias frequency, the nanowire has therefore to be biased at near $1 \times f$ for the field-effect transduction while it has to be biased at $2 \times f$ for the PZR transduction. A simple setup can hence be used with little change for each transduction. It should be noted that the capacitive dynamic current (roughly estimated from $\varepsilon_0 S/g^2 \omega_0 a(\omega_0)$) is between 0.1 and 0.01 pA. It is two to three orders of magnitude lower than the experimental current presented in section 4.

4. High frequency experimental results

4.1. Experimental schemes and techniques

High frequency electromechanical measurements have been performed in a probe station at room temperature for both transduction schemes on the same SiNWs. The readout schemes are based on heterodyne techniques (see figures 3(a) and 4(a)) previously used for SiNW PZR detection [14] or field-effect transduction of carbon nanotubes [29].

In the case of the FET transduction, the transconductance $g_{\rm m}$ is modulated by the bias voltage $V_{\rm Bias}$ at $\omega - \Delta \omega$ since the displacement varies with the AC-actuation $V_{\rm AC}$ at ω . The nanowire acts as a high frequency (HF) mixer—see equation (10) —and the drain current varies at $\Delta \omega$. In the case of the PZR transduction the down-mixing scheme is similar but with an AC-actuation (excitation) at 2ω —see equation (4). For the sake of clarity we will refer to 1*f* when the natural frequency of the nanowire is used and 2*f* for twice its natural frequency.

The biasing and actuation voltages used to operate in the linear regime are similar for the two transduction schemes. V_{Bias} is set between 10 and 150 mV. The AC-actuation V_{AC} is set between 50 and 200 mV since the DC voltage V_{DC} is around a few hundreds of millivolts—300 mV in the example below (i.e., $V_{\text{G}} = 300$ mV for the FET detection). The use of similar voltage values allows a direct comparison of the signal-to-noise (SNR) and the signal-to-background (SBR) ratios obtained with both techniques. The noise spectral power density is also measured for the two transduction schemes to further characterize the noise sources in each case.

4.2. Frequency responses

The results obtained with the PZR transduction show a quadratic variation of the peak amplitude with the actuation voltage (figure 3(b)), while variation with the bias remains linear (figure 3(c)) as expected from equation (4).

As explained above the gauge factor can be estimated from the dynamic drain current by using equation (4). For the operating point ($V_{DC} = 0.3 \text{ V}$, $V_{AC} = 0.1 \text{ V}$, $V_{Bias} = 0.07 \text{ V}$), the drain current at resonance is 10.25 pA. Knowing the initial resistance ($R_0 = 1.2 \text{ M}\Omega$), the actual sizes (SiNW section = 35 nm × 30 nm and length = 2 μ m) and the resonance frequency (67.25 MHz) with a *Q*-factor of 700, the displacement is evaluated at about 1 nm (peak) for an axial stress around 150 kPa. The gauge factor is then close to 200 which matches well with extracted values in the static regime [20].

The theoretical current amplitudes are calculated with the electrical parameter values determined in section 4.1 (i.e., $C_n = 1.95$, $Q_{ss} = 1.5 \times 10^{11}$ cm⁻², $N_a = 4 \times 10^{17}$ cm⁻³) and with a gauge factor of 200. The model shows the right order of magnitude as well as the correct trends.

In contrast, the results obtained with FET transduction show a linear variation of the resonance amplitude when increasing actuation and bias voltages (see figures 4(b) and (c) respectively) as predicted by equation (9). The theoretical current amplitude is calculated assuming the same electrical parameters as for the PZR transduction. The *Q*-factor extracted from the measurement is set to 700 and the resonance frequency is set at 67.27 MHz. g_m is calculated with equation (8). The theoretical results are in a good agreement with the experimental values, showing that a simple model can predict the order of magnitude of the electromechanical response.



Figure 3. Piezoresistive transduction of SiNW resonators. (a) Readout scheme used for PZR transduction. The nanowire is biased with a 2ω signal as the resistance variation due to the second-order PZR effect, while actuation is performed at 1ω . The output signal is detected with a lock-in amplifier (LIA). A low pass filter (LPF) is used to reject parasitic frequencies coming from mixer and RF synthesizers. RF-signals are split with two power splitters (PS). (b) Electromechanical resonances for various actuation voltages V_{AC} . The amplitude varies quadratically with the actuation voltage as expected from theory. (c) Electromechanical resonances for various bias voltages V_{Bias} . The amplitude is linear with the bias voltage.

These results have been obtained on the same device. The SBR for the FET transduction is of the order of 2.5 depending on polarization conditions whereas the SBR in the case of the PZR transduction is of the order 4.5. Results obtained with various devices are shown in supplementary information (available at stacks.iop.org/Nano/24/435203/mmedia). Systematic measurements led to the conclusion that the PZR detection seems to be slightly (about 50%) more efficient than the FET-detection scheme.

As discussed in previous sections, one of the main motivations here is the development of a smart, compact SiNW pixel unit for potential resonant mass sensing with such pixel arrays. Like for any other application involving resonant detection, the frequency stability $\delta f/f_0$ of such a pixel is a key property. One usual estimation of this frequency stability is the Allan deviation [30] σ_A versus an integration time τ . For dominant amplitude white noise and narrow integration bandwidth $1/\tau$ compared to the eigen-frequency ω_0 , σ_A follows an asymptotic law:

$$\frac{\delta f}{f_0}(\tau) = \frac{1}{2Q} \frac{\sqrt{1/\tau}}{\text{SNR}}.$$
(10)

The frequency fluctuation measurements have been performed on the N67MHz resonator with both transduction mecha-



Figure 4. High frequency transduction of SiNW resonators via the embedded field-effect transistor. (a) Readout scheme used for field-effect transduction of the resonant nanowire. In this case, both actuation and bias are 1ω -signals. The pick-up of the output signal is performed with a LIA as in the PZR case. (b) Electromechanical resonances for different actuation voltages V_{AC} . The amplitude variation is proportional to the actuation voltage as expected from theory. (c) Electromechanical resonances for various bias V_{Bias} . The amplitude is linear with the bias voltage.

nisms. The Allan deviation is measured in open loop recording the phase variation of the drain current [10].

Allan deviation results of the two transduction schemes are presented figure 5, with integration times in a range of practical use for most applications. They are following a $\tau^{-1/2}$ power law, in agreement with equation (10). This shows that white noise processes are dominant over this whole range of integration times. In the FET-detection case, the slope seems to inflect at 1 s-integration time due to 1/f-noise appearance. In the studied case, the thermomechanical noise is estimated at 0.044 pm Hz^{-1/2}, which corresponds to 1.13 fA Hz^{-1/2} and 22 fA Hz^{-1/2} for the PZR and FET transduction respectively, thus remaining negligible. The Johnson noise is the second obvious white noise process. Its magnitude is estimated at 0.043 pA Hz^{-1/2} by measuring its spectral power density with a PXI (peripheral component interconnect for instruments) card. The lock-in amplifier exhibits a white noise density of 0.13 pA Hz^{-1/2}, which is the dominant noise process in the measurement scheme. As the PZR detection is more efficient—current amplitude of 17.5 pA against 4.5 pA for the FET detection for the same operating points—it offers an improved short-term frequency stability versus that obtained



Figure 5. Frequency stability (Allan deviation) measured in both PZR and field-effect transduction schemes. The suspended SiNW is driven at its resonant frequency at the onset of the non-linearity (resonance signals are 17 pA and 4.5 pA for PZR and FET transductions respectively). The Allan deviation is measured in three steps (for short, intermediate and long times). For short times (<0.05), the integration time of the lock-in and the global acquisition time are 100 μ s and 1 s respectively. For intermediate times (0.05 s $< \tau < 0.5$ s), they are set to 100 μ s and 10 s respectively. For long times (0.5 s $< \tau < 5$ s) they are set to 1 ms and 100 s respectively. These adjustments remove the effect of the lock-in filtering that would artificially decrease the Allan deviation and ensure at least 20 points for each interval. They follow a clear $\tau^{-1/2}$ power law, which shows that white noise processes are dominant over the whole range of integration times. The best Allan deviation in this range is close to 3 ppm with the PZR transduction while it reaches up to 20 ppm with the FET transduction.

with a FET transduction (see equation (10)). The best Allan deviation in our time range is close to 3 ppm with the PZR transduction while it reaches up to 20 ppm with the FET transduction. This is also the case for the nanowire resonating at 145.5 MHz shown in SI (available at stacks.iop.org/Nano/24/435203/mmedia). The Allan deviation results obtained with the PZR transduction on many devices are comparable to results presented by Bachtold *et al* [8], with frequencies in the GHz range, but at liquid helium temperatures.

In conclusion, we have experimentally demonstrated some of the smallest top-down SiNW NEMS resonators, with minimum width down to ~ 20 nm, and resonance frequencies up to 150 MHz, in the mid-upper very high frequency (VHF) band. This was achieved thanks to a top-down, 200 mm VLSI process fully amenable to monolithic CMOS co-integration, as was demonstrated elsewhere with first-order PZR devices [17, 31]. The very small dimensions have allowed for the first realization of a vibrating SiNW NEMS, where the conductance is controlled by a nearby gate without junction. The electrical performance of such fieldeffect detection has been compared to the self-transducing piezoresistive scheme within the same SiNW. Both schemes have shown similar SBRs, and the PZR transduction has exhibited a slightly higher output signal. As the dominant source of noise in both cases is the input noise of the LIA, independent from the transduction type, the PZR one shows a correspondingly better SNR. Frequency stability of the same SiNW has been measured with both transductions, and we obtain 20 ppm for the FET detection and 3 ppm for the PZR detection at ambient temperature and low pressure. Piezoresistive gauge factors have been measured with two distinct methods (static and dynamic regimes), which agree well.

In the near future, the junction-less field-effect transconductance will be improved thanks to efforts on the process and geometry (smaller widths and gaps, lead resistance...), as well as on the doping level, at the expense of the gauge factor. Both transduction schemes should hence show very close SNRs; one could consider using both transductions simultaneously to increase the output signal, by using two bias harmonic at the same time. CMOS co-integration, already demonstrated with this very same process, will undeniably boost the SNR of both transductions. Based on our experience, we are confident that Allan deviation of $\sigma_A \sim 1$ ppm can be reasonably reached with such a device (which corresponds to the level set by the Johnson noise). Considering the device effective mass, this translates into a sub-zg $(1 \text{ zg} = 10^{-21} \text{ g})$ mass resolution at ambient temperature and a few seconds integration time. An order of magnitude improvement is to be expected when operating at low temperatures, yielding a limit of detection of the order of 50 yg (1 yg = 10^{-24} g). Only bottom-up devices like graphene nano-ribbons [32] or carbon nanotubes [8] have reached similar or better mass resolutions. These performances combined with a VLSI-, CMOS-compatible process open up new sensing paradigms: the compact, simple topology of this elementary pixel is ideally suited for ultra-dense arrays. This is of paramount importance for increased capture cross-section for gas sensing [13] or real-world NEMS mass spectrometry systems [12]. Also, a variety of applications within the More-Than-Moore framework will benefit from the array topology, like logic switches [5] or RF receivers [33] where each NEMS is a channel; if noise processes are uncorrelated, an N-device array will provide a \sqrt{N} increase in SNR, which is particularly interesting for time keeping [4] for instance.

Acknowledgments

The authors acknowledge financial support from the European Commission under the FP7 STREP NEMS-IC program and Grant Agreement No. 224525. P X-L Feng acknowledges partial support from the Case School of Engineering. We thank Carine Marcoux for her helpful work on the fabrication technology.

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High Frequency Top-Down Junction-less Silicon Nanowire

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Geometries of several tested suspended nanowires measured by SEM (Scanning Electron Microscope) are presented in table S1.

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 Table S1:
 The geometry of the designs characterized. The thickness of the silicon is the same for all devices

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Resistivity Measurements

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Figure S1: Nanowire resistance with respect to the length for cross-sections of 40×29 nm². The extracted resistivity is 0.076Ω ·cm, corresponding to a Boron doping concentration of 3.77×10^{17} cm⁻³.

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versus dopant concentration obtained from the computation are presented in Figure S2. Values are close to common bulk data. From the measured resistivity we can extract the dopant concentration close to 4×10^{17} cm⁻³ while the targeted dopant concentration was fixed at 10^{19} cm⁻³. Actually the depletion effect that tends to reduce the real conduction section is the main explanation to this deviation. For the smaller section, the dopant deactivation may also impact on the real amount of active dopants participating to the conduction. These effects are well detailed in the paper of Björk¹.



Figure S2: Resistivity (dark line) and mobility (blue line) versus dopant concentration – Theoretical values are very close to common bulk values available in the literature.

Gauge factor measurement

By using the method described in Ref 2, gauge factors of our nanowires were measured. Typical resistance variations according to the strain are presented in Figure S3 for three SiNWs with the same geometrical and material specifications (1 μ m long, 36 nm wide, 38 nm thick and dopant concentration ~ 5×10¹⁷ cm⁻³). The resistance change is quite linear over the entire strain range ±8x10⁻⁴ (i.e. ±135 MPa). In the presented case the extracted gauge factor is 80(±5) when the nanowire is not

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Figure S3: Resistance variation with strain of a 1 μ m long, 36 nm wide and 38 nm thick nanowire – The dopant concentration was set at 5×10¹⁷ cm⁻³.

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Finite Element Method (FEM) computations of hole concentration in nanowires according to $V_{\rm G}$ and $V_{\rm DS}$ are made. Simulations with the software COMSOL are based on the so-called drift/diffusion assumption of holes and electrons. In this example we consider the device N120MHz (width=80nm & gap=80nm). The surface charge density is set at 2.5×10^{11} C.cm⁻² since the dopant concentration is set at 7×10^{17} cm⁻³. Typical results are shown in Figure S4 a) & b) for a drain voltage $V_{\rm D}$ =-1.5V. The depletion of the channel is completed when applying a gate voltage larger than 19V (see Figure S4 b)). By the way this value is in agreement with the experimental values. The Figure S5 shows the drain current with respect to the gate voltage for the same conditions. The curve in the figure S5 shows similar trend compared to the experimental results. The surface charge density used here is also used for analytical computation based on the equation (9) in the main text.





Figure S4: 2D-Comsol simulation showing the hole concentration along the nanowire N120MHz for a) $V_G=0V$, b) $V_G=19V - V_{DS}=-1.5V$.



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$$C_i = C_n \frac{\varepsilon_0 t}{g}$$

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Figure S6: 2D-mapping of voltage distribution between gates and SiNW – Arrows are the electrostatic field lines.

DC-Characteristics of the Junction-less Suspended Silicon Nanowire -

$I_{\rm DS}(V_{\rm DS})$ Characteristics

Measurements of static drain current versus drain voltage characteristics have also been made on several SiNWs. For example $I_{DS}(V_{DS})$ characteristics for different gate voltages for the nanowire N67MHz are presented in Figure S7. Theoretical fits obtained from the equation (9) (see the main text) are superimposed. The only parameters that are tuned to fit the experimental data are N_a and the surface charge density Q_{ss} set at 4×10^{17} cm⁻³ and 2×10^{11} cm⁻² respectively.



Figure S7: $I_{DS}(V_{DS})$ characteristics for different gate voltages for the nanowire N67MHz.

Resistance Variation of the Junction-less Nanowire with the Gate Voltage

A parameter of interest is the resistance variation with the gate voltage that is directly related to the nanowire displacement when it is vibrating. The relative resistance variation with respect to the gate voltage is shown in Figure S8 for the N67MHz device. This measurement is done for voltages larger than the flat-band voltage up to the depletion. It is interesting to evaluate the relative resistance change around V_{G} ~0.5V because it corresponds to the operating point of the HF-electromechanical measurements. In the inset of the Figure S8, this variation is linear with respect

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to the gate voltage. In this example, the slope $\frac{\partial R}{R_0 \partial V_G}$ (at $V_G=0.7$ and $V_{DS}=100$ mV) is around 4.5 %. R_0

is measured at zero gate voltage.



Figure S8: $dR/R(V_G)$ measurement for low drain voltage (V_D =100mV) on the nanowire N67MHz. Working at low drain voltages corresponds to the rf bias applied for resonance measurements.

Let us go back to equations (9) of the main text, the slope can be explicitly defined,

$$g_{DS} = \frac{\partial I_{DS}}{\partial V_{DS}} = \frac{2t_{Si}}{\rho L} \left[\left(\frac{w_{Si}}{2} - \frac{C_i}{eN_a} (V_G - V_{FB}) \right) + \frac{C_i}{eN_a} V_{DS} \right]$$
$$\frac{\partial R_{DS}}{\partial V_G} = \frac{\frac{2t_{Si}C_i}{\rho LeN_a}}{\left[\left(\frac{w_{Si}}{2} - \frac{C_i}{eN_a} (V_G - V_{FB}) \right) + \frac{C_i}{eN_a} V_{DS} \right]^2}$$
$$\alpha = \frac{1}{R_0} \frac{\partial R_{DS}}{\partial V_G} = \frac{1}{\left[\left(\frac{w_{Si}}{2} - \frac{C_i}{eN_a} (V_G - V_{FB}) \right) + \frac{C_i}{eN_a} V_{DS} \right]^2} \times \frac{4t_{Si}^2 w_{Si} C_i}{\rho^2 L^2 eN_a}$$

Once again if we consider the N67MHz device, the equation above leads to a theoretical value of α close to 3% that is similar to the experimental value (4.5%) for V_{DS} varying between ±100 mV. This

relative resistance change is high enough to get an electrical signal when the nanowire is vibrating at its resonance frequency even if the displacement remains tiny (~1nm).

AC-Electromechanical Measurements on Several SiNWs

As suspended SiNWs have been fabricated with VLSI process, we have been able to test a lot of devices. Typical results are demonstrated in the following Figure S9 – S14. For example electromechanical responses of several SiNWs obtained from FET (at $1 \times f$ measurement) or piezoresistive (at $2 \times f$ measurement) transductions are presented below. Most of the nano devices show good resonances and could be used as part of a sensor.



Figure S9: Device N137MHz – Electromechanical resonance obtained by PZR transduction.



Figure S10: Device N146MHz – Electromechanical resonance obtained by FET transduction.



Figure S11: Device N146MHz – Electromechanical resonance obtained by FET transduction.



Figure S12: Device N146MHz – Electromechanical resonance obtained by PZR transduction.



Figure S13: Device N113.6MHz – Electromechanical resonance measured by FET transduction.



Figure S14: Device N91MHz – Electromechanical resonance obtained by FET transduction

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 C_n is obtained from 2D-FEM simulation with COMSOL software to evaluate the capacitance between a nanowire and a gate and by comparison with the parallel plate capacitor expression. The geometry is as close as possible to the TEM cross section (Figure 1 of the main text). Typical electrostatic field lines are shown in Figure S6 for a 80nm-gap. C_n is estimated around 1.5 and 1.95 for 80nm and 150nm respectively.



Figure S6: 2D-mapping of voltage distribution between gates and SiNW – Arrows are the electrostatic field lines.

DC-Characteristics of the Junction-less Suspended Silicon Nanowire -

$I_{\rm DS}(V_{\rm DS})$ Characteristics

Measurements of static drain current versus drain voltage characteristics have also been made on several SiNWs. For example $I_{DS}(V_{DS})$ characteristics for different gate voltages for the nanowire N67MHz are presented in Figure S7. Theoretical fits obtained from the equation (9) (see the main text) are superimposed. The only parameters that are tuned to fit the experimental data are N_a and the surface charge density Q_{ss} set at 4×10^{17} cm⁻³ and 2×10^{11} cm⁻² respectively.



Figure S7: $I_{DS}(V_{DS})$ characteristics for different gate voltages for the nanowire N67MHz.

Resistance Variation of the Junction-less Nanowire with the Gate Voltage

A parameter of interest is the resistance variation with the gate voltage that is directly related to the nanowire displacement when it is vibrating. The relative resistance variation with respect to the gate voltage is shown in Figure S8 for the N67MHz device. This measurement is done for voltages larger than the flat-band voltage up to the depletion. It is interesting to evaluate the relative resistance change around V_{G} ~0.5V because it corresponds to the operating point of the HF-electromechanical measurements. In the inset of the Figure S8, this variation is linear with respect

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to the gate voltage. In this example, the slope $\frac{\partial R}{R_0 \partial V_G}$ (at $V_G=0.7$ and $V_{DS}=100$ mV) is around 4.5 %. R_0

is measured at zero gate voltage.



Figure S8: $dR/R(V_G)$ measurement for low drain voltage (V_D =100mV) on the nanowire N67MHz. Working at low drain voltages corresponds to the rf bias applied for resonance measurements.

Let us go back to equations (9) of the main text, the slope can be explicitly defined,

$$g_{DS} = \frac{\partial I_{DS}}{\partial V_{DS}} = \frac{2t_{Si}}{\rho L} \left[\left(\frac{w_{Si}}{2} - \frac{C_i}{eN_a} (V_G - V_{FB}) \right) + \frac{C_i}{eN_a} V_{DS} \right]$$
$$\frac{\partial R_{DS}}{\partial V_G} = \frac{\frac{2t_{Si}C_i}{\rho LeN_a}}{\left[\left(\frac{w_{Si}}{2} - \frac{C_i}{eN_a} (V_G - V_{FB}) \right) + \frac{C_i}{eN_a} V_{DS} \right]^2}$$
$$\alpha = \frac{1}{R_0} \frac{\partial R_{DS}}{\partial V_G} = \frac{1}{\left[\left(\frac{w_{Si}}{2} - \frac{C_i}{eN_a} (V_G - V_{FB}) \right) + \frac{C_i}{eN_a} V_{DS} \right]^2} \times \frac{4t_{Si}^2 w_{Si} C_i}{\rho^2 L^2 eN_a}$$

Once again if we consider the N67MHz device, the equation above leads to a theoretical value of α close to 3% that is similar to the experimental value (4.5%) for V_{DS} varying between ±100 mV. This

relative resistance change is high enough to get an electrical signal when the nanowire is vibrating at its resonance frequency even if the displacement remains tiny (~1nm).

AC-Electromechanical Measurements on Several SiNWs

As suspended SiNWs have been fabricated with VLSI process, we have been able to test a lot of devices. Typical results are demonstrated in the following Figure S9 – S14. For example electromechanical responses of several SiNWs obtained from FET (at $1 \times f$ measurement) or piezoresistive (at $2 \times f$ measurement) transductions are presented below. Most of the nano devices show good resonances and could be used as part of a sensor.



Figure S9: Device N137MHz – Electromechanical resonance obtained by PZR transduction.



Figure S10: Device N146MHz – Electromechanical resonance obtained by FET transduction.



Figure S11: Device N146MHz – Electromechanical resonance obtained by FET transduction.



Figure S12: Device N146MHz – Electromechanical resonance obtained by PZR transduction.



Figure S13: Device N113.6MHz – Electromechanical resonance measured by FET transduction.



Figure S14: Device N91MHz – Electromechanical resonance obtained by FET transduction

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