Self-excitation of single nanomechanical pillars

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Abstract. Self-excitation is a mechanism that is ubiquitous for electromechanical power devices such as electrical generators. This is conventionally achieved by making use of the magnetic field component in electrical generators (Nedic and Lipo 2000 IEEE/IAS Conf. Records (Rome, Italy) vol 1 pp 51–6), a good and widely visible example of which is the wind turbine farm (Muljadi et al 2005 J. Sol. Energy Eng. 127 581–7). In other words, a static force, such as the wind acting on rotor blades, can generate a resonant excitation at a certain mechanical frequency. For nanomechanical systems (Craighead 2000 Science 290 1532–5; Roukes 2001 Phys. World 14 25–31; Cleland 2003 Foundations of Nanomechanics (Berlin: Springer); Ayari et al 2007 Nano Lett. 7 2252–7; Koenig et al 2008 Nat. Nanotechnol. 3 482–4) such a self-excitation (SE) mechanism is also highly desirable, because it can generate mechanical oscillations at radio frequencies by simply applying a dc bias voltage. This is of great importance for low-power signal communication devices and detectors, as well as for mechanical computing elements. For a particular nanomechanical system—the single electron shuttle—this effect was predicted some time ago by Gorelik \textit{et al} (Phys. Rev. Lett. 80 4526–9). Here, we use a nanoelectromechanical single electron transistor (NEMSET) to demonstrate self-excitation for both the soft and hard regimes, respectively. The ability to use self-excitation in nanomechanical systems may enable the detection of quantum mechanical backaction effects (Naik et al 2006 Nature 443 193–6) in direct tunneling, macroscopic

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quantum tunneling (Savelev et al 2006 New J. Phys. 8 105–15) and rectification (Pistolesi and Fazio 2005 Phys. Rev. Lett. 94 036806–4). All these effects have so far been overshadowed by the large driving voltages that had to be applied.

Electron shuttling in semiconductor nanostructures was demonstrated in different configurations of the nanoelectromechanical single electron transistor (NEMSET) [3, 4]. The main limitation in resolving quantum mechanical effects, such as Coulomb blockade (CB) of electron transport, is given by the excitation mechanism: an ac driver signal applied to the source electrode leads, via the resonant Coulomb force (RCF) mechanism [5, 6], to the onset of mechanical resonance at the eigenfrequency of a NEMSET. However, the signal level commonly required is of the order of several volts, thus overshadowing CB effects. For an estimate of the Coulomb energy, we can use the orthodox CB model, which relates the total capacitance of the pillar \( C = C_s + C_d \) to the charging energy \( E_C = e^2/2C_S \). This in turn gives an energy of about 30 meV for a small metallic NEMSET of some 10 nm diameter (with a typical capacitance of some 10 aF). This is just sufficient to reveal CB at room temperature; however, it has to be combined with a proper excitation mechanism for mechanical resonances, such as self-excitation.

The current generation of NEMSETs is processed as nanopillars and placed in a microwave coplanar wave guide between two metallic contacts in silicon-on-insulator wafer material. On top of the 50 nm wide and 300 nm tall pillars, a thin layer of gold is deposited, functioning as the electron island (see figure 1). In contrast to earlier work [4, 7], the nanopillars we are investigating here possess resonance frequencies at the lower end of the radio frequency (RF) spectrum. This is due to the more ‘mushroom’-like shape of the pillars, as can be seen in figure 1(a). We anticipated that with such a shape the regime of self-excitation can be established more easily.

In order to test both regimes of self-excitation, we fabricated nanopillars in different gate geometries (termed flat and sharp in the following), which translates into soft self-excitation (SE) and hard SE, as outlined in the theory by Gorelik et al [1]. In essence, it is a competition between the electric field energy \( \sim \omega = 2\pi f \) and a dc bias) and the mechanical energy \( \sim \omega_m = 2\pi f_m \). In altering the gate geometry, we have chosen to primarily vary the effective electric field applied to the nanopillar, while using pillars of similar shape.

In the following we first focus on the analysis of soft SE where the nanopillar is placed between two flat electrodes, as shown in figure 1(a). In order to have a good understanding of the effect of a single nanopillar on the transmission through such a contact, we also fabricated a second sample without a pillar (see figure 1(b)), termed ‘gap’. The samples are placed in a probe station with high-frequency probe tips (dc—50 GHz). The probe station is evacuated to a pressure of 10\(^{-4}\) mbar and all measurements are performed at room temperature. Both devices are placed in a coplanar wave guide for probing the electromechanical response versus RF applied (see figure 1(c)). Commonly, an RF synthesizer is combined with a dc bias \( V_{dc} \) via a bias-tee to drive the sample capacitively with a voltage \( V_{ac} \) at frequency \( \omega_0 \). This induces a mechanical displacement via RCF excitation [5, 6] if the RF signal matches a mechanical eigenfrequency of the nanopillar \( \omega_m \). Depending on the amplitudes of \( V_{ac} \) and the bias voltage \( V_{dc} \), a current \( I_D \) of some 10 pA to 10 nA is shuttled from the drain to the source. Finally, the current is amplified with a standard current amplifier.

For determining the mechanical self-excitation, we made use of the intrinsic signal mixing properties of the NEMSET, i.e. the nonlinear characteristic: conventionally two phase-locked synthesizers with a combined output signal \( \{V_{ac}^0(\omega_0) + V_{ac}^1(\omega_1)\} \) are applied to the input port.
Figure 1. (a) Scanning electron microscope picture of the nanopillar between two electrodes. The diameter of the pillar is 60 nm with a height of 250 nm—on the top, a 45 nm gold layer is added. (b) Two-electrode configuration without a nanomechanical structure forming a simple gap for control measurements. The gap width is 110 nm. Note that the electrodes for both samples are forming flat capacitor plates. (c) CPW with nanopillar in the center and measurement circuit: at the source S, a signal generator provides the ac voltage $V_{ac}(t)$ at an incident power $P$ and at frequency $\omega$ with a superimposed dc bias. The reference signal $\Delta \omega = |\omega - \omega_m|$ is generated by mixing the incident electromagnetic signal at $\omega$ with the mechanical eigenfrequency $\omega_m$ of the nanopillar. Self-excitation is characterized by detecting the LIA signal and the net current at drain D with a current amplifier.

of the sample with a nonlinear IV characteristic [7, 8]. The difference frequency defined by $\delta \omega = |\omega_1 - \omega_0|$ or multiples of it is the mixing product, which can be used as a reference for the lock-in amplifier (LIA). Here, we do not focus on the signal mixing process itself (which we describe in detail elsewhere [8]), but make use of the same principle for probing self-excitation: we apply one electromagnetic signal at $\omega_0$, but then use the mechanical frequency $\omega_m$ of the nanopillar (self-excited via the dc bias voltage) as the second component of the mixing signal. It has to be noted that the electromagnetic RF signal is applied at sub-threshold and only triggers the mixing process. Here, a sub-threshold signal is referred to when the ac-voltage amplitude...
Figure 2. (a) The direct current through the junction versus bias voltage $V_{\text{bias}}$; (b) the Fowler–Nordheim plots with the nanopillar and without (gap). The onset of current flow for the nanopillar appears to be an order of magnitude below that for the gap, as expected. Both plots indicate that the nanopillar strongly distorts the electromagnetic field and enhances the effective field strength purely by geometry.

is leveled at around 2 V, below the threshold of $\sim 4$ V required for the onset of a current (see figures 2(a) and 3). Hence, the ac signal alone will not cause self-excitation. The threshold itself is given by the mechanical stiffness (its Young’s modulus) of the nanopillar. The signal that finally results can then be traced with the LIA at the reference frequency $\Delta \omega = \omega_0 - \omega_m$. This approach ensures that we can accurately monitor self-excitation, as will be shown below. We need to stress that this mixing method is slightly different from the one applied independently by He et al [9] and Sazonova et al [10], in that we are only applying one electromagnetic signal that is mixed with the intrinsic mechanical resonance.

The single nanopillar is placed in a coplanar waveguide (CPW) for improved impedance and hence power matching. Transport of electrons occurs by shuttling via the nanopillar; that is, electrons tunnel onto the metallic island on top of the pillar when it is close to the source contact and then leave the pillar once it is close to the drain electrode. In addition to conventional tunneling, this electron shuttling mechanism is supported by thermionic emission and field emission. The effective field enhancement supporting field emission via the electron shuttle is documented in the data for the flat electrodes shown in figure 2: the $IV$ characteristic of the nanopillar (no RF applied) is compared with the characteristic of a CPW junction without a nanopillar. Obviously, electron transport has a strongly reduced threshold with the nanopillar in place by a factor of five. This is clear evidence for the control of electron transport by the
Figure 3. Mechanical self-excitation of the nanopillar in the soft limit: 
(a) Direct current $I_D$ at mechanical resonance of $\omega_m/2\pi = f_m = 10.5$ MHz under conventional ac drive with a large amplitude of $V_{ac}(\omega)$. The different traces indicate the increase of the dc bias leading to a rising resonance peak and an increase in background current. (b) Full bias dependence of the direct current at mechanical resonance measured at 300 K and $10^{-4}$ mbar. Comparison of $V_{dc}$ ($V_{ac} = 0$, black trace) to a dc bias with a sub-threshold ac signal applied (red trace). The ac signal’s amplitude is $\sim 2$ V. (c) Mixing signal obtained with this ac signal (at $\omega$ and dc bias increased—the individual traces are offset for clarity). The mixing signal is directly proportional to the mechanical displacement and is only detected with the lock-in when the difference frequency of the electrical sub-threshold signal and the mechanical frequency match: $|\omega - \omega_m| = \Delta \omega$. (d) Bias dependence of the self-excitation signal with a power-dependent voltage relation according to $V_{bias}^{1/2}$, as predicted by Iscasson et al [11]. The onset of shuttling is clearly identified to be at 4 V, i.e. when the nanopillar resonates at its fundamental mode and leads to a mixing signal $G_{mix}$. The threshold voltage is indicated by $V_{th}$; the onset can be clearly distinguished in contrast to the direct current recording in (b). This is due to the fact that the mixing signal truly relies on mechanical displacement only, while the direct current contains contributions from field-emitted electrons.
nanopillar. Detailed description of field emission and the mechanical resonance spectra is given elsewhere \cite{6,8}. Clearly visible is also the strongly nonlinear $IV$ characteristic. The dominance of field emission is underlined in figure 2(b), where the traces from figure 2(a) are plotted in the standard Fowler–Nordheim fashion. As expected, field emission is strongest for large bias voltages $V_{\text{bias}}$, whereas for small bias, conventional tunneling through the nanopillar prevails. From the extrapolation of the solid lines, we obtain an order of magnitude difference between the pure gap ($\sim 40 \text{ V}$) and the nanopillar junction ($\sim 4 \text{ V}$) for the onset for field emission.

The next step in the measurements is to probe the current spectra of the nanopillar: in figure 3(a), the response of the nanomechanical resonator to an ac excitation is shown in the direct current $I_D$. An ac signal of $19 \text{ dBm}$ is superimposed to the dc bias varied from 0 to 16 V. This is the standard mechanism for excitation of nanopillars based on the RCF method. The resulting apparent resonance at $\omega_m/2\pi = 10.5 \text{ MHz}$ is fairly broad with a mechanical quality factor around $Q \sim 2.5$. Per cycle of mechanical motion of the nanopillar, it shuttles on average $\langle n \rangle = \langle I \rangle / 2e$ electrons, where $e$ is the elementary charge. For a current of $350 \text{ pA}$ at the resonance of $\sim 10 \text{ MHz}$, shown in figure 3(a), we obtain an average number of $\langle n \rangle \sim 100$ electrons per cycle. Hence, the mixing signal is determined by single electrons being shuttled from the source to the drain.

Having shown that the $IV$ characteristic is nonlinear and that the nanopillar can be excited by an electromagnetic ac signal, we can now apply signal mixing. It is important to note that we probe self-excitation, i.e. instead of two electromagnetic signals, we apply a single sub-threshold ac signal ($\omega$) and mix this with the mechanical eigenfrequency of the nanopillar at $\omega_m$. The threshold voltage for the nanopillar used in this experiment is at $V_{\text{th}} = 4 \text{ V}$. Phase-sensitive detection of a resulting signal at the offset frequency $\Delta \omega$ implies that the mechanical mode is indeed induced by the dc bias and hence is evidence for self-excitation. The first step in this direction is shown in figure 3(b), where we compare a pure dc bias (black trace) with a superimposed $\{V_{\text{dc}} + V_{\text{ac}}\}$. It is important to note that the effective signal strength of $V_{\text{ac}}$ is now below the threshold for RCF excitation of a mechanical resonance (see figure 3 for details).

It appears clear that we supply the necessary energy for self-excitation by the dc electric field. However, one could still argue that a rectification effect is predominant. Hence, only probing the highly sensitive mixing signal given as $G_{\text{mix}} \sim d^2I/dV^2 \cos(\Delta \omega t)$ will provide the necessary information that it is indeed a mechanical displacement induced by a dominant dc voltage. In figure 3(c) this mixing signal is plotted versus the probing ac frequency with the different traces corresponding to dc bias values (traces are offset for clarity). As pointed out before, these traces are obtained from phase sensitively amplifying the lock-in signal at $\Delta \omega$ under the condition $|V_{\text{dc}}| < |V_{\text{th}}|$ (see figure 3(b)). The mechanical $Q$-factor obtained from these measurements appears to be of the order of $\sim 7$, better than the one found in the direct current. This is most likely related to the fact that the mixing signal $G_{\text{mix}}$ is directly proportional to the displacement $x$, but neglects field-emitted electrons, which are not directly associated with a mechanical motion. In other words, the direct current determined in figure 3(a) shows shuttling of electrons, but also a contribution from field-emitted electrons (as in standard RCF excitation). Using this more sensitive mixing technique, which relies on mechanical displacement of the nanopillar, we can now directly state the relation $G_{\text{mix}} \sim x$. This effect corresponds to self-excitation of the nanopillar in the soft limit \cite{1}.

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In figure 3(d), the detailed bias dependence of the self-excitation signal $G_{\text{mix}}$ under increasing ac signal power is plotted. As predicted by Isacsson et al [11], the traces follow a $V_{\text{bias}}^{1/2}$-dependence from the sharp onset of mechanical motion on, i.e. when the nanopillar resonates at its eigenfrequency. This is indicated by the fit (dashed lines). The threshold voltage is marked by $V_{\text{th}}$ with the onset at $V_{\text{bias}} \sim 4$ V. Obviously, the onset can be clearly identified in contrast to the direct current recording in figure 3(b). This imprecision of the measurement in $I_D$ is due to the fact that the mixing signal truly relies on mechanical displacement, while the direct current contains contributions from field-emitted electrons.

As predicted by Isacsson et al [11], there exist two cases of self-excitation: the hard and the soft limit. Basically, the hard limit reveals a bistable state, which appears as a hysteresis in the IV characteristic. The distinction between the hard and soft limits can be analyzed by comparing the electronic energy, which is fed into the nanopillar by a constant bias voltage, while the nanopillar is oscillating at the mechanical energy ($\sim \omega_m$). In order to address the hard SE limit, we altered the initially used electrode geometry by choosing a sharp electrode as source contact—see figure 4(a). Again a coplanar wave guide is used with the center lead being the signal line. We then placed two nanopillars—diameters of 60 nm (left) and 30 nm (right)—close to the signal line (see lower left inset). For the measurements we have chosen the left nanopillar, because the diameter is comparable to the ones used to study the soft limit of SE.

The competition between the electronic and the mechanical degrees of freedom then leads to a single stable mechanical resonance for the soft limit (flat electrode geometry) and a bistable state for the hard limit (sharp electrode geometry). The lower right-hand side inset in figure 4(a) gives a numerical simulation of the electric field distribution between the two electrodes and the nanopillar. The color coding shows the field strength; as expected the highest field intensity is found between the sharp electrode and the pillar (red), while the lowest intensities are found off the central symmetry axis at $y = 0$. As seen in the scanning electron microscope picture, we can assume a slight misalignment of the nanopillar. The total energy of the nanopillar in such an electric field is sketched in the upper right-hand side inset: the pure mechanical elastic energy will follow Hooke’s law with $E_m = (1/2)\kappa r^2$, with $\kappa$ being the restoring spring constant and $x^2 + y^2 = r^2$ the actual displacement from equilibrium (dashed black line). The sharp electrode now leads to an electrical field energy that is not symmetrical as compared with the flat electrode geometry: it shows a spike with increasing voltage (dash-dotted blue line). The total electromechanical energy is then given by the superposition of both contributions (solid red line). As seen, a slight misalignment of the nanopillar with respect to the electrodes is sufficient to lead to an asymmetry between the two stable states $\alpha$ and $\beta$ of the system. More precisely, the paths $\alpha$ and $\beta$ correspond to the two different mechanical modes.

In figures 4(b) and (c), two consecutive bias sweeps on the nanopillar are shown. The red trace in figure 4(b) was the initial measurement, while the blue trace (c) is taken after several sweeps. As seen, we find the predicted hysteresis in both measurements. The width of the hysteresis is a direct measure of the energy difference between potential wells $\alpha$ and $\beta$, which is of the order of 2 eV (arrows in figure 4(c)). Such a bistability can be applied for memory applications or for probing entanglement in such a nanomechanical system, as suggested by Savelev et al [2]. For reaching the quantum limit, the device has to be cooled to mK temperatures and the mechanical eigenfrequency has to be increased to the GHz regime, which appears to be possible [12].

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Figure 4. Mechanical self-excitation in the hard limit: (a) Coplanar wave guide with an alternative sample geometry. As the lower left inset shows, an electrode geometry was chosen with a sharpened electrode in contrast to the flat electrodes used before. The nanopillar dimensions of the left pillar are similar to the sample used for probing self-excitation in the soft limit (see figure 1(a)). The lower right-hand side inset shows a numerical simulation of the electromagnetic field distribution between the two electrodes and the nanopillar. As found in the electron micrograph, we assumed a slight misalignment of the pillar. The total energy of the nanopillar in such an electric field is sketched in the upper right-hand side inset: the pure mechanical elastic energy will have a square dependence on the spatial coordinate $r^2 = x^2 + y^2$ (dashed black line). Increasing the electric field builds up the potential indicated by the dash-dotted blue line. The superposition of both yields the total energy (solid red line) revealing two potential minima $\alpha$ and $\beta$. In (b) and (c), two consecutive bias sweeps on the nanopillar are shown. The red trace in (b) was the initial measurement, whereas the blue trace (c) shows the hysteresis after several sweeps. The width of the hysteresis is a measure of the energy difference between potential wells $\alpha$ and $\beta$.

In summary, we have demonstrated how to probe self-excitation in a nanomechanical system by using mechanical mixing. This has apparent applications as a mechanical mixer for communication electronics, because the realization of a dc-driven mechanical resonance renders an external oscillator obsolete. Especially in conjunction with CB, self-excitation has the potential to open a new regime for quantum electromechanical devices.
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References

[1] Gorelik L Y, Isacsson A, Voinova M V, Kasemo B, Shekhter R I and Jonson M 1998 Shuttle mechanism for charge transfer in coulomb blockade nanostructures Phys. Rev. Lett. 80 4526–9
[2] Savelev S, Hu X and Nori F 2006 Quantum Electromechanics: qubits from buckling nanobars New J. Phys. 8 105–15
[3] Erbe A, Weiss Ch, Zwerger W and Blick R H 2001 Nanomechanical resonator shuttling single electrons at radio frequencies Phys. Rev. Lett. 87 096106–4
[4] Scheible D V and Blick R H 2004 Silicon nanopillars for mechanical single-electron transport Appl. Phys. Lett. 84 4632–4
[5] Scheible D V, Weiss C and Blick R H 2004 Effects of low attenuation in a nanomechanical electron shuttle J. Appl. Phys. 96 1757–62
[6] Scheible D V, Weiss C, Kotthaus J P and Blick R H 2004 Periodic field emission from an isolated nanoscale electron island Phys. Rev. Lett. 93 186801–4
[7] Kim H S, Qin H, Westphall M S, Smith L M and Blick R H 2007 Field emission from a single nanomechanical pillar Nanotechnology 18 065201–4
[8] Kim H S, Qin H and Blick R H 2007 Single electron mechanical mixing in a nano-electromechanical diode Appl. Phys. Lett. 91 143101–3
[9] He R R, Feng X L, Roukez M L and Yang P D 2008 Self-transducing silicon nanowire electromechanical systems at room temperature Nano Lett. 8 1756–61
[10] Sazonova V, Yaish Y, Ustunel H, Roundy D, Arias T A and McEuen P L 2004 A tunable carbon nanotube electromechanical oscillator Nature 431 284–7
[11] Isacsson A, Gorelik L Y, Voinova M V, Kasemo B, Shekhter R I and Jonson M 1998 Shuttle instability in self-assembled coulomb blockade nanostructures Physica B 255 150–63
[12] Peng H B, Chang C W, Aloni A, Yuzvinsky T D and Zettl A 2006 Ultrahigh frequency nanotube resonators Phys. Rev. Lett. 97 087203–4