Sensing of single electrons using micro and nano technologies: a review

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Abstract

During the last three decades, the remarkable dynamic features of microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS), and advances in solid-state electronics hold much potential for the fabrication of extremely sensitive charge sensors. These sensors have a broad range of applications, such as those involving the measurement of ionization radiation, detection of bio-analyte and aerosol particles, mass spectrometry, scanning tunneling microscopy, and quantum computation. Designing charge sensors (also known as charge electrometers) for electrometry is deemed significant because of the sensitivity and resolution issues in the range of micro- and nano-scales. This article reviews the development of state-of-the-art micro- and nano-charge sensors, and discusses their technological challenges for practical implementation.

Keywords

electrometer, charge sensor, resolution, single-electron transistor (SET), MEMS/NEMS resonator, vibrating-reed

1. Introduction

The sensing of single electrons, in terms of electrostatic charge or miniature current, is measured by a device called a charge sensor (which is also known as a charge electrometer). Contacting (direct) and non-contacting (no physical or electrical contact) measurements are two different methods that are used to detect electrostatic charge. Charge sensors or charge electrometers are widely used for direct measurement of electric charge or extremely small current [1]-[2]. On the other hand, a number of non-contacting electrostatic voltmeters and electric field meters have been used for many years to measure the surface charge of any test object [3]-[8]. Highly sensitive charge electrometers are prevalent in many diverse applications. These include: mass spectrometry; surface charge analysis; ionization current measurement in ionization chambers as well as radiation or particle detection of nuclear studies; and various applications of powder technology and aerosol science [9]-[12]. Such electrometers are also used in a number of precision applications, such as tunneling microscopy; ultrafine particles measurement; bimolecular and electrochemical charge detection; and even space exploration [13]-[17].

In the early twentieth century, Millikan demonstrated the quantitative electromechanical measurement of electrostatic charge (1 electron $\approx 1.60217733 \times 10^{-19}$ C) by using an “oil drop” experiment [18]. In that experiment, he charged a tiny drop of oil and measured how strong an applied electric field had to be in order to stop the oil drop from falling. By varying the charge on different drops, he was able to find the charge of a single electron. Before the advent of modern active electrometers, such as early valves (vacuum tubes) and semiconductor transistors, different types of passive electrometers were widely used. These are described elsewhere [2], [19]. Of these, the gold-leaf electroscope, Coulumb’s electrometer, and Kelvin’s quadrant electrometer were the most popular. Nowadays, compared to these classical electrometers, high resolution charge electrometers (together with electronic devices and signal conditioning circuitries) are exploited for translating electrostatic charge or very tiny current into electrical signals. Traditionally, the charge of a small object or piece of material is measured by placing it in a Faraday cup or pail (or

Faraday cage) along with a sensitive electrometer. This cup acts as a shielded sensing electrode of the electrometer, and consequently, the object induces an equal magnitude of charge, but of an opposite sign on the surface of the cup (inner cup) [20]-[21].

The Keithley 6517A (a commercial solid-state electrometer) is well-known for its minimum resolution of 10 fC ($\approx 63,000$ electrons) [22]. However, for bespoke scientific applications, this resolution is insufficient to meet scientific needs. One of the reasons for the low resolution and moderate sensitivity of this instrument is due to the preamplifier's built-in input noise, i.e. preamp noise. In sensitive charge measurement techniques, it is inevitable to avoid the noise caused by this pre-amplifier. Operational amplifier based readout circuits (used in existing electrometers), such as a transimpedance amplifier (TIA), a charge amplifier, and a resistive gain amplifier, exhibit three common electrical noises: Johnson noise, shot noise and flicker noise in different bandwidths of operation [23]-[24]. Due to these noise effects, the sensitivity and the resolution of these kinds of commercial electrometers are limited. Hence, requirement of low-noise, high sensitive charge sensors or electrometers is nowadays essential for precise measurement of electrostatic charge. Currently, charge sensing can be carried out using cutting-edge nanoelectronic devices, such as field-effect transistors (FETs), single-electron transistors (SETs), and quantum point-contacts (QPCs). Additionally, the charge sensors can be implemented by resonance type MEMS/NEMS devices and micromachined vibrating-reed type devices due to the advancement of nanomaterials and semiconductor processes.

In this paper, we review the charge detection mechanism of miniature electrometers, specifically the mesoscopic single-electron transistor (SET); the NEMS and MEMS based resonant sensors; and the MEMS based vibrating-reed sensors. This review will allow us to determine the practical attributes of each mechanism in different technologies by focusing on the resolution and noise characteristics.

2. Mesoscopic Single-Electron Transistor (SET) Electrometer

The single-electron tunneling transistor (SETT) or single-electron transistor (SET) is deemed the most fundamental nanoscale single-electron device (SED) due to its capability of manipulating just one electron [25]-[27]. It gains its name by utilizing the quantum

phenomenon of tunneling to measure and control the movement of single electrons inside a solid-state circuit. Due to the exceptional progression of nanoelectronics in the last two decades, SETs as solid-state electrometers are out-performing conventional metal-oxide semiconductor field-effect transistors (MOSFETs) based electrometers by three orders of magnitude in terms of charge resolution [28]-[29]. A three-terminal SET includes a source, a drain, a gate, and a minuscule channel region known as conductive island or quantum dot (QD) or Coulomb blockade island (made by metals or compound semiconductors or carbon nanotubes or graphene) [30]-[33]. This conductive island is isolated from the source and drain by two tunnel junctions or barriers (e.g. SiO_2) (figure 1). Employing a small voltage across a tunnel junction of a SET, it behaves like a tunnel capacitor. However, electrons tunnel through this barrier, which can be explained intrinsically by a quantum mechanics phenomenon illustrated in [26]-[27], [31].

Figure 1. (a) Block diagram of SET as a charge electrometer (b) scanning-electron micrograph image of Al based SET [30]

If a constant voltage is applied to a tunnel junction of a SET, periodic current pulses are produced. The small total capacitance of the Coulomb blockade and the discreteness of the electric charge instigate the current to behave as a periodic function of the gate charge with a period of one electron charge. This occurrence results in Coulomb blockade oscillations (CBO). By adding a positive or negative charge directly to the island, the CBO characteristic is shifted by one period along the gate voltage axis. These gate voltage (δV_g) changes, corresponding to sub-electron variations of q_{in} , cause a measurable change in source-drain current (I_{SD}) through modulating the transconductance, $g_m = \delta I_{SD} / \delta V_g$. Thus, to achieve

maximum gate voltage sensitivity, conventional SETs are biased to a point of maximum g_m . In this sense, the SET is considered a highly sensitive, miniaturized electrometer, which can easily sense a fraction of the elementary (sub-single electron) charge by the change in its characteristics (if the charge is placed close to the conducting island or QD) [31].

Krupenin *et al.* demonstrated conventional Al-SET electrometers with charge resolution down to $8 \times 10^{-6} \text{ e}/\sqrt{\text{Hz}}$ at 10 Hz [34]. The resolution of $8 \times 10^{-6} \text{ e}/\sqrt{\text{Hz}}$ means that the charge of $8 \times 10^{-6} \text{ e}$ on the SET gate of the electrometer can be detected against the noise in a 1-s measurement. The charge resolution of DC-SET can be represented as $\delta q/\sqrt{\Delta f} = [\sqrt{2eI_{DS}} \cdot \sqrt{S_I(0)}]/G_m$. Here, G_m is charge gain, $S_I(0)$ is the normalized zero-frequency noise [35]. High resolution of the sensor can be achieved by reducing the total noise spectral density and by improving the sensitivity of the device. Although this resolution was high, it was evaluated at a low frequency, where the flicker noise predominates in the system hiding small signals. In most experiments involving the SET, the noise at low frequencies is dominated by the device itself, whereas external sources set the noise limit for frequencies above the kHz regime. Owing to the small bandwidth and this extra noise contribution, the predicted charge resolution is difficult to achieve. Besides the flicker noise, two other types of noise affect the performance of SETs: shot noise and amplifier noise [36]. The resolution of this nano-transistor is mostly be limited by the shot noise generated when electrons tunnel across the tunnel barriers. The shot noise is observed in a two-junction structure without a gate. In the SET, the noise is believed to be caused by a small, two-level system, either in close proximity to the conducting island or inside a tunnel barrier.

To overcome the flicker noise problems and detect fast charge fluctuations, a technique that incorporates the Al-based SET into a radio-frequency resonant circuit (*i.e.* LC tank circuit denoted as RF-SET) is better than conventional DC-SETs [29], [32], [37]-[38]. By using this technique, a charge resolution of $1.2 \times 10^{-5} \text{ e}/\sqrt{\text{Hz}}$ was recorded at a signal frequency of 100 MHz [29]; on the other hand, using a resolution bandwidth of 15 kHz, Brenning *et al.* measured a high charge resolution of $1.9 \times 10^{-6} \text{ e}/\sqrt{\text{Hz}}$ at a temperature of 4.2 K [38]. Instead of measuring the output current or voltage, this reflectometry technique monitored the damping of the resonant circuit. It has the advantage of substantially reducing low-frequency flicker noise due to the high operating frequency. A single-wall carbon nanotube (SWNT) RF-SET based electrometer proposed by Tang *et al.* achieved a charge resolution of $4.8 \times$

$10^{-4} e/\sqrt{\text{Hz}}$ at 30 Hz bandwidth, as shown in figure 2 [32]. The transistor's sensitivity performance was improved by reducing the two-junction area and island size compared to its Al based RF-SET counterpart. Angus *et al.* developed a silicon based RF-SET and achieved an even better resolution of $10 \times 10^{-6} e/\sqrt{\text{Hz}}$ using at 15 MHz bandwidth [39]. Employing Si/SiGe quantum dots (QDs) with a radio frequency superconducting single-electron transistor (RF-SSET) detected excellent charge resolution of $4 \times 10^{-6} e/\sqrt{\text{Hz}}$ at 1 kHz bandwidth, with an SNR of 27.5 dB [40]. The charge resolution of RF-SETs is determined using following expression: $\delta q = \Delta q_{rms} / [10^{SNR/20} \cdot \sqrt{2B}]$. Here, Δq_{rms} is the applied root mean square gate charge, B is the resolution bandwidth of the spectrum analyzer, $\sqrt{2}$ accounts for the fact that there are two side peaks, and SNR is the signal to noise ratio in dB [38].

Figure 2. Schematic diagram of the RF-SET measurement setup [32]

In SETs, the tunneling of electrons through the junction barrier depends on the electrostatics of the system. Electrons can tunnel into the island only if the charging energy associated with adding the electrons to the island is overcome. The electrostatic charging energy of a single island SET is defined as $E_c = e^2 / (2C_{total})$; where, C_{total} is the summation of two junction capacitances and one gate capacitance [31]. It is essential that this energy is overcome before an electron can tunnel onto the island, and the external applied bias (V_{ds}) provides the energy for tunneling. To observe single electron tunneling, low temperature operation is required. Otherwise, the tunneling process can be activated thermally without external bias because of

thermal energy $K_B T$. At room temperature (300K), the thermal energy could be sufficiently higher than the electrostatic charging energy E_c , thereby reducing the charge resolution.

There are two strategies to stop the tunneling process caused by the thermal effect. The first strategy is to reduce the thermal energy by lowering the temperature. For example, restricting the cryogenic temperature regime of SETs can make the thermal energy $K_B T$ below the charging energy E_c . However, cryogenic temperature operation needs bulky and costly equipment and has been one of the main technological obstacles affecting the advancement and proliferation of these devices as practical charge sensors [41]. The second strategy is to increase the charging energy E_c to be more than thermal energy $K_B T$ at room temperature for the room temperature operation. As $E_c = e^2 / (2C_{total})$, the charging energy can be increased by reducing C_{total} to significantly small values, for example around atto-farad range or even less. To achieve 1 aF capacitance, the island dimension is required to be reduced to less than 10 nm. Therefore, feature size of existing electron beam lithography, optical lithography or even focus ion beam lithography need to be improved to shrink the island size of the SET, maintaining sufficient charging energy to operate at room temperature [42]. In addition, implementation of multiple tunnel junction (MTJ), *i.e.*, serially connected multiple-island system in the SETs, is another plausible means of reducing C_{total} for room temperature operation [43]-[44]. Recently, Si-FET based electrometer, one of the competitors of the SET electrometers, demonstrated by Nishiguchi *et al.* (fabricated on an SOI substrate), exhibits a resolution of $13 \times 10^{-4} \text{ e}/\sqrt{\text{Hz}}$ (@ 1 Hz) at room temperature [45]. Later on, Nishiguchi *et al.* achieved even better resolution of $2 \times 10^{-4} \text{ e}/\sqrt{\text{Hz}}$ with higher bandwidth of 20 MHz at room temperature due to high SNR of 21 dB. This was achieved by using RF-FET comprised of a nanometer-scale Si-FET with an impedance-matching circuit made up of a capacitor and an inductor by reflectometry technique [46].

Voltage gain in SETs is difficult to achieve at room temperature because the gate capacitance must be made larger than the junction capacitance while making the total capacitance small. For the SET, it is more relevant to consider the charge gain, which is a frequency dependent quantity. This charge gain is the modulation of the charge that passes through the SET divided by the change in charge on the gate. Incidentally, a charge gain of greater than one can be achieved at room temperature [47].

The background charge or offset charge problem is another important issue, which is inhibiting the extensive use of SETs [30]-[31]. In SETs, the background charge fluctuations

result in phase shifts of the output voltage. The same kinds of charged defects are identified in nano-scale FETs. However, most of the conventional MOSFETs are not sensitive charge detectors. Therefore, the consequences of background charges are not effective for MOSFETs. One of the most effective strategies to compensate for this problem is SETs is to use the conventional MOSFETs along with SET electrometers to tune out background charges.

The large output impedance of a DC-SET (operating at room temperature) of at least 100 k Ω makes this transistor an intrinsically slow device. To speed up the charge measurement, conventional MOSFETs of CMOS processes should be placed as close as possible to the SETs, buffering the high output impedance of the SETs. Until a practical scheme is developed, the best way to proceed is to use the SETs only as sensitive charge sensors and perform all other functions with conventional high speed MOSFETs [31]. In order to realize high-density functional circuits using SETs, it is essential to have a reliable nano-fabrication technology that enables fabrication of a large number of SETs. Nonetheless, due to the low current drive of the SETs, hybrid SET-MOSFET circuits seem to be more useful than all-SET circuits. Thus, fabrication technology of the SETs as charge sensors, which are still in the exploratory phase at room temperature, have to be compatible with existing downscaling standard CMOS processes (*e.g.* 14 nm, 10 nm).

3. Resonant Electrometer

In a typical MEMS/NEMS resonant sensor, the resonator's natural frequency is a function of the measurand (or disturbances or stimuli). An input disturbance typically changes the stiffness, mass and geometric shape of the resonator, thus initiating an alteration in its resonant frequency [48]-[57]. The dynamic properties of a high natural frequency, high quality factors (Q) and minuscule mass have established resonant MEMS/NEMS as improved types of sensors [58]-[63]. The natural frequency (f_x) of the resonant device (*e.g.* paddle resonator) is represented as (both for translational and torsional mode) [60],

$$f_x = \frac{1}{2\pi} \sqrt{\frac{k_{eff}}{m_{eff}}} \quad (1)$$

where, k_{eff} = effective spring constant and m_{eff} = effective mass or inertia of the paddle.

In electromechanical sensing applications, coupling the resonator to the charge is achieved by applying electrostatic force (ESF) or a strain across the structure. Both the vibration (excitation) mechanism and detection mechanism are significant in the design of a resonant sensor. The vibration mechanism excites the vibrations in the structure of the resonator element, while the detection mechanism senses these vibrations in the form of frequency. Finally, the frequency of the detected vibration develops the output of the sensor in the form of voltage, as shown in figure 3. A high Q factor is demanded for the MEMS/NEMS resonator based charge sensor, for which the sensor's resolution (or limit of detection) is limited by the smallest detectable change in resonant frequency. Here, the control system of the resonator can be implemented either by an open or closed loop (*i.e.* the signal is fed back to the drive mechanism via a sustaining amplifier).

Figure 3. Block diagram of a typical resonant MEMS/NEMS charge sensor with a closed-loop system

3.1 NEMS based resonant electrometer

Before the advent of modern electrostatic charge detection techniques (in 1785), Charles-Augustin de Coulomb introduced the first electromechanically, torsion-based electrometer [65]. After approximately 200 years, Cleland & Roukes proposed a novel fabrication and performance analysis of a NEMS based electrometer, as shown in figure 4 [66]. Nowadays, nano-electro-mechanical systems (NEMS) have demonstrated their effectiveness in both basic science and industrial applications, due to overcoming the limitations of macro- and micro-scale devices [67]-[74]. Utilization of state-of-the-art NEMS resonant sensors (under

conditions of vacuum and cryogenic temperature) in many scientific applications is a consequence of the ultra-small mass and size of the resonator; ultra-high natural resonance frequencies; ultra-high sensitivities for very small stimuli; ultra-low power consumption for actuation forces; and ultra-fast response time to applied forces.

Figure 4. NEMS based charge sensor using a torsional resonator [66]

For a torsional resonator type NEMS sensor, the magnetomotive technique has been utilized for both actuation and detection [66]. While a static magnetic field is applied perpendicular to both the two-element torsional resonant structure and the current, the resonator is excited by an alternating current due to the Lorentz force. The resulting motion of the resonator through the magnetic field generates an electromotive force that is detected by the measurement circuitry. Principal components of this sensor are a double torsion mechanical resonator, two detection electrodes, and a gate electrode used to couple charge to the mechanical element. The resonator was fabricated from a single crystal Si-on-insulator substrate, with a 0.2 mm thick Si layer on a 0.4 mm insulating layer. The gold loop electrode and resonator structure are patterned using Electron Beam Lithography (EBL). This NEMS fabrication method is known as the top-down approach, using semiconductor processing technology.

Like any mechanical resonators, key figures of merit of the NEMS resonators are resonance frequency, Q factor, dimensions, geometrical structures and materials for fabrication. The resonator described in [66] is a double paddle torsional or two-element torsional resonator, which has a very high Q factor (6500) characteristic, and thus exhibits low phase noise performance. To measure a small charge, the gate electrode is biased by a charge yielding an electrostatic force (ESF). While the bias point is considered as q_0 and small changes in the

charge are considered as δq , the bias point alters the ESF by an amount of $2\delta q E_0$, where E_0 = equilibrium electric field. The principle of electrometry in this research is the change in the resonance frequency due to the charge modulation of the effective torsional spring constant; therefore, frequency modulation detection has been employed to obtain a responsivity or sensitivity measurement.

The high Q factor (*i.e.* less energy dissipation) of the device means it exhibits high sensitivity and high resolution [73]. To enhance the Q factor for achieving high resolution in resonant sensors, the damping needs to be minimised. Compared to typical MEMS dimensions of resonant sensors, this NEMS sensor has reduced structured dimensions, and thus thermoelastic damping (TED) has a negligible effect and total energy dissipation declines. The torsional element on the resonator also alleviates clamping or anchor loss to enhance the Q factor. Here, a thermal noise analysis indicates that such an NEMS resonator based electrometer exhibits resolution of the order of 10^{-6} e/ $\sqrt{\text{Hz}}$. This very high resolution makes the device competitive with the cryogenic SET electrometers, but with important added advantages of higher temperature operation and the ability to respond over a greatly increased bandwidth. Due to a high fundamental resonance frequency of 2.61 MHz, the mechanical Johnson noise effect is insignificant in this case.

Blick *et al.* [75] have introduced another NEMS based charge sensor, which significantly enhances the speed of charge detection by using a clamped beam as a translational (flexural) resonator (figure 5 (a)). The device has been fabricated on an SOI substrate by a combined dry- and wet-etched process. In this nanomachined electromechanical resonator based sensor, a low-power radio frequency propagates through a suspended beam of Si covered with a thin layer of gold. This frequency sets it into vibration. With an in-plane magnetic field applied perpendicular to this straight beam, a Lorentz force perpendicular to the substrate surface is developed, which in turn sets the resonator in the motion. The two gates on both sides of the beam are biased capacitively to detune the resonator's eigen-frequency. Application of a voltage (V) between the center gates and the beam, induces a charge (q) on the beam resonator via the relation: $q = CV$. This essentially modifies its stiffness or spring constant under a low temperature of 4.2 K with ^4He -gas pressure of approximately 10^{-2} bar. This results in a mechanical resonance frequency shift, Δf . When RF power steers the resonator to the verge of nonlinear amplitude vibration, optimum charge detection (maximum frequency shift) can be obtained. For a gate bias of ± 4 V, a magnetic field of 12 T, and an RF power of -

52.8 dBm at 37.29 MHz, a charge detection resolution of $70 \text{ e}/\sqrt{\text{Hz}}$ is achieved. The high resolution of $1 \text{ e}/\sqrt{\text{Hz}}$ can be elevated further by implementing the mixer and phase shifter used in [66]. Bunch *et al.* fabricated an inimitable graphene based translational resonant charge sensor exhibiting a resolution of $8 \times 10^{-4} \text{ e}/\sqrt{\text{Hz}}$ at 300 K but at very low pressure of $<10^{-6}$ torr [76]. They used single- and multilayer graphene sheets by mechanically exfoliating thin sheets from graphite over trenches in SiO_2 (figure 5(b)). However, at the expense of both optical/electrical actuation and optical interferometer detection, it did not achieve monumental resolution compared to [66] because of operating at room temperature.

(a)

(b)

Figure 5. NEMS based charge sensor using a translational resonators (a) suspended Si [75] (b) suspended graphene [76]

The magnetomotive technique on a NEMS resonant charge sensor is advantageous for detecting charge sensitivity. Nevertheless, it is particularly limited by the requirement of comparatively strong magnetic fields (8 Tesla in [66] or 12 Tesla in [75]), which are typically

achieved with superconducting coils at liquid helium temperature. Though these techniques are suitable for low temperature experiments of charge sensing in the fundamental research of metrology, these methods are not realistic for commercial applications. This is due to high costs, inefficient integration techniques of CMOS and NEMS technologies, large measurement setups and portability issues. In addition, the bandwidth achieved by [66] is limited to only 400 Hz, owing to uncontrolled parasitic capacitances. Integration of mechanically flexible nano-structures with SEDs on a nanometer-scale is an exciting prospect in nano-electrometer design. Unlike conventional SETs and resonant NEMS charge sensors, a SWNT-SET resonant sensor was recently introduced by Hakkinen *et al.* (figure 6). This quantum electromechanical sensor has demonstrated a better resolution of $0.97 \times 10^{-6} e/\sqrt{\text{Hz}}$ (@ 1.3 kHz) at a temperature of 50 mK [77].

Figure 6. SWNT-SET NEMS resonant sensor (a) SEM image of device with a suspended CNT between source and drain electrodes (b) measurement setup [77]

Frequency stability is a key concern for the performance of nano-resonators and their applications. Frequency stability at the resonance frequency of these resonators can be affected by the noise added to the signal amplitude, which provokes jitters in the phase. This noise can induce spectral broadening and fluctuations in the resonance frequency. The

resolution of the resonant sensors not only depends on the Q factor but also is limited by the dynamic range (DR). The relation between frequency stability $\langle \delta f / f_0 \rangle$, Q factor and DR of the resonator device can be presented as $\langle \delta f / f_0 \rangle = 1 / (2Q) \times 10^{-DR/20}$ [78]. Here, DR is expressed as the ratio between the maximum driven signal level and the noise floor (dB). Based on this relation, we can conclude that higher Q factor and wider DR can improve the frequency stability.

Thus, one strategy to reduce phase noise is to increase Q factor. High Q factor of NEMS resonators can be achieved if the following major damping effects can be minimized: (1) thermoelastic damping (TED); (2) air damping due to the viscous drag or molecular collision; (3) anchor or clamping loss near the anchor of the resonator; (4) Akhiezer effect or loss; (5) phonon-tunneling dissipation; (6) surface loss due to surface imperfections [55], [57]. For instance, TED can be alleviated if the device size is reduced, and it is more prevalent in MEMS devices. However, design optimization is required for NEMS resonators so that downscaled resonator elements do not exhibit nonlinearity during sensing; the sensors can be operated at low pressure to avoid air damping to attain high Q; the clamping loss of [76] could be reduced if suspended element is designed for in-plane motion rather than out-of-plane motion. One promising way of increasing Q factor artificially in NEMS resonators is to introduce parametric amplification [69].

Another strategy to reduce the phase noise is to increase the dynamic range by minimizing the noises in the overall system. Independent multiple noise sources, categorized as extrinsic noises and intrinsic noises, contribute to the phase noise degradation of high-resolution resonant charge sensors. Intrinsic phase noise sources include thermomechanical noise contributed from random Brownian motion, adsorption-desorption noise, and temperature fluctuations due to the finite thermal conductance of the resonating device [79]. Thermomechanical force spectral density of NEMS resonator (per unit bandwidth) can be expressed as $S_F = (4M_{eff}\omega_0 K_B T) / Q$ [76]. Here, the ultimate limit on the force resolution S_F is proportional to the temperature T and inversely proportional to the Q factor. Therefore, low temperature and high Q are desirable to reduce the intrinsic phase noise. However, extrinsic noises arising from read-out circuitries are more dominant compared to the intrinsic noises in the sensing systems. For example, voltage and current noises in the pre-amplifier and corresponding biasing and gain components in [66] could exhibit significant noise magnitude at room temperature. Due to these setbacks of low Q factor and high noise, the

aforementioned NEMS resonators as charge sensors are preferred to operating at cryogenic temperature and very low pressure to achieve high charge resolution.

3.2 MEMS based resonant electrometer

The advent of micromachining and micro-electromechanical system (MEMS) technologies over four decades has enabled the development of various types of reduced sized sensors. Among these, the micromechanical resonant sensors have exquisite sensitivity and resolution. These sensors are used to manage a wide range of measurands, such as acceleration, density, mass, force, displacement, temperature, strain as well as the electrostatic charge [80]-[87].

Lee *et al.* designed a resonant MEMS based electrometer using the principle of axial strain modulation and a single-crystal silicon double-ended tuning fork (DETF) resonator as a charge-sensing element, as shown in figure 7 [88]. While the measurand (*i.e.* the charge) is coupled as an axial force along the longitudinal axis of the DETF, a charge across an input capacitor induces a tensile axial strain in the resonating tines (or parallel beams) resulting in a shift in resonant frequency. As shown in figure 7(a), one end of the DETF is anchored and the other end is physically constrained in the horizontal axis. To avoid out-of-plane motion, lateral guiding beams are located on each side. A charge actuation electrode is located adjacent to the free end of the DETF, forming the input of the electrometer. The tines are driven laterally in the anti-phase through parallel gap actuation electrodes attached on each tine. As the tines are forced into their primary mode of operation, the corresponding changes in the sense gaps generate a motional current at the sense electrodes, which is applied by transimpedance amplifier (TIA). For closed loop measurement setup of the electrometer, the TIA is followed by an active bandpass filter and a comparator forming a nonlinear oscillator circuit topology, which is capable of sustaining oscillations within large feedthrough limits. Both actuation and detection has been realized capacitively. In this electrometer, a minimum measurable charge of 4 fC has been achieved at room temperature. This sensor's high sensitivity performance is due to a high Q factor of 80,000 at room temperature and a very low pressure of 4 mTorr. By using a balanced mode structure like DETF, the sensor significantly alleviates clamping loss to enhance the Q factor, thus the DETF structure is popular for designing a resonator based electrometer [88]-[89]. The resonant sensor was

fabricated through a commercial silicon-on-insulator (SOI)–MUMPS foundry process from MEMSCAP [90].

Figure 7. Single DETF resonator based MEMS electrometer (a) schematic diagram with open-loop measurement setup (b) scanning-electron micrograph image [88]

The responsiveness of the silicon DETF resonator could also be enhanced through mechanical force leverage systems, *i.e.* micro-leverage mechanisms (micro-levers) capable of amplifying an input force, as shown in figure 8 [91]. Utilizing the similar design principle of [88], dual micro-levers are exploited to enhance the sensitivity by the mechanical amplification. This mechanical amplifier neither adds significant Brownian noise nor influences the electronic noise level of the interface circuitry. The measured responsiveness of this electrometer has been achieved at $1.3 \times 10^{-3} \text{ Hz/fC}^2$. The resolution of the proposed charge sensor is 21 fC under 4 ppm frequency fluctuations. Zhao *et al.* further investigated this sensor by adding an adjustable or calibrated MEMS capacitor near the input charge electrode to achieve a high charge resolution of 0.84 fC and a large dynamic range [92]. Both of these single crystal Si-resonant charge sensors were fabricated by the SOIMUMPs commercial process. Though sensing paradigms of [91] and [92] have key advantages, such as easy implementation and high resolution, DC bias (or tuning) voltages are comparably larger than [88] in these electrometry techniques. Moreover, these measurement setups have been implemented for open-loop systems rather than closed-loop systems. In measurement setups, the variable frequencies (of actuation signal) were produced by a network analyzer (figure 8(a)). Then, TIA amplified and converted the motional current to the voltage, and finally voltage signal fed to the same network analyzer. The performance of these types of

resonant MEMS charge sensors is also limited by extrinsic phase noise (due to readout circuit) and intrinsic phase noise (such as temperature fluctuation noise, gas desorption and adsorption noise), significantly affecting both the short and long-term frequency stability.

Previously mentioned resonator based MEMS/NEMS charge sensors except ref [88] require the support of an external oscillator to compensate for energy losses; otherwise, these resonators will gradually stop oscillating. By exploiting an electronic feedback loop including an amplifier, filter, phase shifter and amplitude limiter, a closed-loop self-sustaining MEMS/NEMS oscillator can be obtained without using an external oscillator. Using closed-loop measurement to track the resonance frequency of the resonators can achieve high frequency resolution and dynamic range compared to open-loop methods (such as frequency sweep, amplitude or phase-shift variation). Like NEMS resonator based sensing devices, the resolution of MEMS sensing system also suffers mainly due to electronic noises (white noise and flicker noise) of the readout circuits compared to the intrinsic noises. Phase noise is the crucial indicator of the total noise level in an oscillator and related to the resolution. In a Leeson-type model for an oscillator, the phase noise, $\mathcal{L}(f)$ is written as [93]

$$\mathcal{L}(f) = 10\log\left\{\left(\frac{2F_n k_B T}{P_c}\right) \cdot \left[1 + \left(\frac{f_0}{2Qf}\right)^2\right] \cdot \left[1 + \left(\frac{f_{1/f^3}}{f}\right)\right]\right\} \quad (2)$$

where, f is the frequency offset from the carrier resonance frequency f_0 , f_{1/f^3} is corner offset frequency of the active devices used in the oscillator, P_c is the carrier signal power; F_n is noise factor of the active devices, k_B is Boltzmann's constant, T is absolute temperature in degrees Kelvin.

According to the equation (2), there are a few strategies to obtain lower phase noise in the MEMS resonator based self-sustaining oscillator, for example, higher Q factor, lower resonance frequency, higher carrier output power and lower temperature. In addition, by reducing flicker noise up-conversion and white noise (total root sum square of uncorrelated shot noise and Johnson noise) of the electronic circuitries, better phase noise performance can be achieved. Furthermore, the phase noise in [88] can be improved by synchronizing the nonlinear oscillator (in which resonant MEMS charge sensor is embedded) with the help of a weak external harmonic signal [94].

(a)

(b)

Figure 8. Single DETF resonator type MEMS electrometer with micro-leverage mechanism (a) schematic diagram with open-loop measurement setup (b) scanning-electron micrograph image [92]

Micromechanical resonant electrometers can be implemented not only by the single resonators but also the mode localization coupled resonators. Mode-localized resonator based electrometers utilize weakly coupled resonators (WCRs), which can be formed either electrostatically or mechanically [95]-[96]. Mode localization phenomenon is realized in a periodic system *i.e.* nearly identical WCRs. The presence of a small perturbation in the initially balanced system of WCRs prevents the long-range propagation of vibration. The tiny symmetry breaking perturbation of the structure causes extreme vibration of energy confinement. The vibration depends on both the magnitude of the induced order and the strength of the internal coupling between the WCRs. This weakly coupling between the resonators results in strong localization of the vibration modes.

Thiruvengatanathan *et al.* proposed the first 2-DOF electrically coupled mode localization MEMS electrometer, in which eigen-state or amplitude ratio was chosen as the output metric, and high sensitivity was achieved [97]. In the design, two electrostatically weakly coupled DETF resonators were used as a charge sensing element. Based on this principle, Zhang *et al.* modified the charge sensing element, in which a pair of DETF resonators was weakly coupled by a mechanical beam, as shown in figure 9(a) [98]-[99]. By decreasing mechanical coupling factor, the sensitivity of the sensor was increased, and thus better charge resolution of 1.269 fC was achieved at temperature of 300 K and pressure of 20 mTorr [99]. Only the out-of-phase mode of each DETF resonator has been detected by placing the sensing electrodes in the centre of the two vibration tines (figure 9(b)). To adjust the effective stiffness of the two DETF resonators, four tuning electrodes around the two resonators are utilized. Two charge input electrodes are located adjacent to one end of resonator 2 forming a couple of charge actuation capacitors. When an external charge is applied to the charge input electrodes, the electrostatic strain acts on the resonator 2, and the effective stiffness of this resonator 2 will be altered. On the other hand, the resonator 1 will remain unchanged because of the absence of input charge. This is how breaking the initial symmetry occurs, and it causes the phenomenon of the mode localization. Finally, measurement of charge resolution can be obtained by measuring the variations of the amplitude ratios of the WCRs. This charge sensor was developed in SOI technology.

The mode-localized resonance principle can improve the sensor's sensitivity in comparison with conventional single resonant sensors. Moreover, owing to the differential configuration, this type of resonator has common mode rejection abilities. However, implementation of mode-localized charge sensors in a self-oscillating loop is a challenging issue. For all mode-localized sensors, the frequency of the actuation signal has to be adjusted locating the vibrational modes, and it is not practical in the sensory applications. It is also imperative to reduce the fluctuations of signal amplitude for the improvement of the sensor's resolution. Furthermore, geometry of the sensor device, the fabrication process, reduction of noise in the readout circuit and the measurement setup need to be improved for high resolution of mode-localized based resonant MEMS charge sensors.

(a)

(b)

Figure 9. Mode-localized DETF resonator type MEMS electrometer (a) scanning-electron micrograph image (b) schematic diagram with open-loop measurement setup [99]

4. Vibrating-reed Electrometer

To avoid flicker noise at low frequencies or near DC levels, a vibrating-reed (vibrating-capacitor) electrometer is a suitable alternative to the previously discussed charge sensors [100]-[104]. In a MEMS vibrating-reed electrometer, a mechanical arrangement moves one of the two plates or comb drives of the dynamic-capacitor at a fixed frequency, f_m [105]. This capacitor has been built between a moving electrode acting as a vibrating reed and a fixed input electrode. Typically, the electrodes can be either parallel plates or comb drives. When an external unknown amount of charge q_{in} (or any small DC voltage representing the charge to be measured) is deposited on the parallel-plate immovable electrode, it is converted to an

alternating voltage signal of frequency, f_m as a consequence of the modulation of the resonating or dynamic-capacitor, C_v . In other words, capacitance of the resonating-capacitor is varied by some external force in a cyclic manner to produce an AC voltage (V_{AC}) proportional to the charge on that capacitor, *i.e.* $q(t) = C_v \cdot V_{AC}$. Once the process has sufficiently amplified signal, a peak-detecting circuit, a synchronous demodulator (*e.g.* lock-in amplifier), or some other circuit that measures the envelope of the modulation frequency and rejects the carrier, can turn the signal into a representation of the DC input charge. Due to the effect of charge feedthrough and flicker noise at low frequencies, the detection circuit is designed to operate at twice the drive frequency ($2f_m$).

Charge sensitivity detection by Reihl *et al.* employed a vibrating MEMS capacitance electrometer composed of an electrostatic comb drive actuator and sense parallel plate capacitors in ModMEMS process [106]. In the design, a charge resolution (charge noise floor) of approximately $28 \text{ e}/\sqrt{\text{Hz}}$ was achieved at 300 K and in ambient pressure. One of the plates on a parallel plate capacitor is allowed to oscillate at a fixed frequency (f), as shown in figure 10(a). This integrated-electrometer consists of three parts: differential actuators, differential motion detector, and charge modulation parallel-plate capacitors. An electrostatic charge collected in an electrode is modulated at the MEMS electrometer drive frequency and at higher harmonics, due to the nonlinear nature of parallel plate capacitors. Feedthrough interference from drive signals to the sensed charge is reduced by designing the charge capacitor (C_c) and the detection electronics to measure a signal at twice the drive frequency (or some other multiple), where the feedthrough signal is minimized. This technique provides the benefit of separating the charge drive signal from the output signal, allowing for easy charge measurement. Designing such a CMOS-MEMS sensor device reduces parasitic effect significantly. An application specific IC (ASIC) as a buffer circuit has been introduced in the design with an input bias current of 5 atto-amperes. This circuit is a remedial of not to drain of the input charges by the bias current of the voltage gain amplifier. Nonetheless, under broad input range and various ranges of operating temperature, the bias current needs to be evaluated in this design for the correct measurement of charge resolution.

Figure 10. Different MEMS based vibrating-reed type charge sensing techniques [106]-[109]

Removing the buffer amplifier from the charge input node and replacing it with a capacitor to couple the input signal, Zhu *et al.* revealed a hybrid MEMS vibrating-reed electrometer [107]. The achievable charge resolution of the sensor is $52.4 \text{ e}/\sqrt{\text{Hz}}$ (figure 10(b)). Another micro-machined hybrid vibrating-reed electrometer proposed by Lee *et al.* achieved a charge resolution of $6 \text{ e}/\sqrt{\text{Hz}}$ (figure 10(c)) [108]. Since the ultimate charge resolution of the electrometer is limited by the thermal electronic noise of the JFET input, a large responsiveness value is desirable in this demonstration. By altering the low noise readout amplifier to alleviate input-referred noise and parasitic capacitance, the sensitivity can be improved to achieve a resolution of $23 \text{ e}/\sqrt{\text{Hz}}$ for sensitive aerosol electrometry applications, as shown in figure 10(d) [109]. One limitation of the vibrating-reed electrometry is the bandwidth by the presence of the large time constant at the input, *i.e.* it takes some time to respond adequately to the step function. Besides this shortcoming, the MEMS vibrating-reed

electrometer has long-term drift and achievable high resolution in inexpensive design facilities of existing MEMS technologies.

MEMS vibrating reed sensing element along with the analog front-end readout circuits are main contributors of the total noise, which impedes achieving high charge resolution of the sensing system. The moving plate of the micromechanical variable capacitor is a mechanical resonator with a micro-meter scale range of motion modulating relatively small electrical signal. Mechanical noise is mainly thermomechanical or Brownian noise due to the random thermal motion of mechanical elements. The damping coefficient of Brownian noise at resonance frequencies of 5 kHz to 10 kHz yields a pico-meter range Brownian noise displacement, and thereby generating infinitesimal electrical signals. Thus, the pico-meter range motions of micromechanical variable capacitor due to Brownian motion have insignificant contribution for charge resolution limitation of these sensors. By contrast, the white noise and flicker noise in the signal conditioning circuitries can significantly deteriorate the charge resolution. Therefore, implementing low leakage current and noise readout amplifier will ensure high-resolution charge sensing capability.

Summary and Perspectives

Apart from charge resolution, the superiority of the charge sensor can be described based on the following features: (i) the sensor output instantaneously attains the sensed charge value, which provides for fast responsiveness; (ii) the charge in the sensor should not be distorted by itself to ensure impedance matching, *i.e.* avoiding loading effects; (iii) its output signal stays at the measured value without being affected by atmospheric and environmental effects, drifting, other noises and undesirable stimuli (unless the charge itself alters robustness and stability); (iv) low output impedance and high gain ensure high sensitivity and a sufficiently large output signal; (v) its output signal changes linearly in response to the input charge signal; (vi) the power dissipation should be insignificantly low due to the high input impedance. Table 1 shows a summary of empirical results of charge resolution measurements on different micro- and nano-sensors extracted from research papers.

Table 1. Performance comparison among various micro- and nano-charge sensor techniques

Ref.	Charge Sensing Type	Transduction Principle	Functional Materials	Fabrication Technology	Temperature	Pressure	Resolution
[34]	DC SET	Tunneling	Aluminium	EBL	25 mK	–	8×10^{-6} $e/\sqrt{\text{Hz}}$ @ 10 Hz
[29]	RF-SET	Tunneling + Reflectometry	Aluminium	EBL	4.2K	–	1.2×10^{-5} $e/\sqrt{\text{Hz}}$ @ 100 MHz
[38]	RF-SET	Tunneling + Reflectometry	Aluminium	Std. lithography and evaporation technique	4.2 K	–	1.9×10^{-6} $e/\sqrt{\text{Hz}}$ @ 15 KHz
[32]	RF-SET	Tunneling + Reflectometry	SWNT	Std. lithography and evaporation technique	4.2K	–	4.8×10^{-4} $e/\sqrt{\text{Hz}}$ @ 30 Hz
[39]	RF-SET	Tunneling + Reflectometry	Silicon	EBL	10 mK	–	10×10^{-6} $e/\sqrt{\text{Hz}}$ @ 15 MHz
[40]	RF-SET	Tunneling + Reflectometry	Si/SiGe	Shadow evaporation technique	0.3 K	–	$4 \times 10^{-6} e/\sqrt{\text{Hz}}$ @ 1 kHz
[45]	DC FET	Field Effect	Silicon	Lithographic patterning and etching	300 K	–	13×10^{-4} $e/\sqrt{\text{Hz}}$ @ 1 Hz
[46]	RF-FET	Field Effect + Reflectometry	Silicon	Lithographic patterning and etching	300 K	–	$2 \times 10^{-4} e/\sqrt{\text{Hz}}$ @ 20 MHz
[66]	NEMS Torsional resonator	Magnetomotive actuation and detection	SOI	EBL	4.2 K	Vacuum (<mTorr)	$10^{-6} e/\sqrt{\text{Hz}}$
[75]	NEMS Translational resonator	Magnetomotive actuation and detection	SOI	EBL+RIE	4.2 K	1.3 Torr	$70 e/\sqrt{\text{Hz}}$
[76]	NEMS Translational resonator	Electrical/optical actuation and optical interferometer detection	Graphene	Mechanical exfoliating	300 K	< 10^{-6} Torr	$8 \times 10^{-4} e/\sqrt{\text{Hz}}$
[79]	NEMS Translational resonator	Electrostatic actuation and tunnelling detection	SWNT	NEMS + SET	50 mK	–	$0.97 \times 10^{-6} e/\sqrt{\text{Hz}}$
[88]	MEMS Translational resonator	Electrostatic actuation and detection	SOI	Bulk Micromachining (MEMSCAP)	300 K	4 mTorr	4 fC
[91]	MEMS Translational resonator	Electrostatic actuation and detection	SOI	Bulk Micromachining (MUMPS)	300 K	40 mTorr	21 fC under 4 ppm frequency fluctuation

[92]	MEMS Translational resonator	Electrostatic actuation and detection	SOI	Bulk Micromachining (MUMPS)	300 K	–	0.84 fC
[99]	MEMS Weakly coupled resonator	Electrostatic actuation and detection	SOI	Surface Micromachining	300 K	20 mTorr	1.269 fC
[106]	MEMS Vibrating- reed	Electrostatic actuation and detection	SOI	Surface Micromachining (ModMEMS)	300 K	Ambient (Air)	28e @ 0.3 Hz
[107]	MEMS Vibrating- reed	Electrostatic actuation and detection	SOI	Bulk Micromachining (MEMSCAP)	300 K	Ambient (Air)	52.4 e/ $\sqrt{\text{Hz}}$
[108]	MEMS Vibrating- reed	Electrostatic actuation and detection	SOI	Bulk Micromachining (MEMSCAP)	300 K	Ambient (Air)	6 e/ $\sqrt{\text{Hz}}$
[109]	MEMS Vibrating- reed	Electrostatic actuation and detection	SOI	Bulk Micromachining (ThELMA)	300 K	Ambient (Air)	23 e/ $\sqrt{\text{Hz}}$

There are continual scientific and technological interests in investigating minimum charge resolution mechanisms in various disciplines. The main objective of this article is to portray the micro and nano instrumentation features of the techniques used for the measurement of charge resolution and the corresponding design challenges of these techniques. The performance and prospects of recent MEMS based vibrating-reed charge sensors (at room temperature and ambient pressure) is superior to existing commercial macro-scale charge sensors in terms of the resolution; the low manufacturing costs in developed (but not standardized) semiconductor processes; their ability to be integrated with CMOS ICs; and their small packaging sizes [110]. In scaling down from MEMS to NEMS technology, the key challenging features are fabrication of the device, characterisation of the device and readout of the device. Owing to the limitations of micro-fabrication and the resolution concerns, established MEMS charge sensors cannot be scaled down suitably to the nano-scale range. In contrast, researchers around the globe are putting sustained efforts into using various materials and implementing novel fabrication technologies with fewer complications and better reproducibility for measuring the small fraction of electron charge (using the SET electrometer at room temperature). Even though nano-scale resonant charge sensors demonstrate the potential to overcome the resolution issue as compared to standalone SET electrometers (at room temperature), further research is needed to make resonant NEMS charge sensors practical by reducing noise and damping factor, in comparison with their MEMS counterparts.

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