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Subthreshold field emission from thin silicon membranes

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We report on strongly enhanced electron multiplication in thin silicon membranes. The device is configured as a transmission-type membrane for electron multiplication. A subthreshold electric field applied on the emission side of the membrane enhances the number of electrons emitted by two orders of magnitude. This enhancement stems from field emitted electrons stimulated by the incident particles, which suggests that stacks of silicon membranes can form ultrasensitive electron multipliers. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2805015]

Particle detectors rely crucially on electron multiplication, as in photomultiplier and electron multiplier tubes, cathode ray screens and microchannel plates.[1] The multiplication is conventionally achieved by employing secondary electron emission (SEE),[1,2] where an incident particle strikes the surface of the detector and induces the emission of secondary electrons (SEs). The physics behind SEE is found in the various interaction pathways between the incident particles and the solid, e.g., electron-nuclear collisions, electron-electron interactions, and plasmon and phonon excitations.[3,4] SEs are only emitted by pathways that allow them to be excited above the vacuum energy level (E_{vac}). Consequently, the barrier for releasing secondary electrons is determined by the difference between the vacuum energy level and the Fermi level: $\Phi = E_{\text{vac}} - E_F$, the work function. The actual figure of merit for detectors, e.g., electron multipliers, is the secondary electron yield (SEY), which is determined by the nature of the detector material. Naturally, many efforts have focused on achieving high SEY by developing materials with a lower work function, as in a recent report of diamond doped with phosphorus.[5]

It is well known that the external electric field at the surface of a metal or a semiconductor can significantly modify the potential barrier and induce field emission (FE) of electrons.[2] Such studies on field-enhanced SEE can be traced back to the discovery of the Malter effect in 1936.[6] Follow-up experiments on SEE revealed variants of this field effect.[7,8] These experiments were conducted on bulk metallic substrates coated with a thin layer of oxide, where the oxide layer is the key. It is this thin surface layer, which either (a) becomes positively charged to induce field emission from the underlying emitter and leads to long persistence times of SEE or (b) produces avalanches of electrons.

Here we present detailed SEE measurements showing a dramatic enhancement of SEY in thin semiconductor membranes by an applied electric field. The field enables subthreshold electron extraction, increasing the yield by two orders of magnitude. We probe this effect in a transmission-type configuration, where the back side of the membrane emitter is bombarded by a primary electron beam (e beam). This approach permits the probing of electronic excitation at low energies, which are otherwise not detectable by conventional SEE.

The device we fabricated is a thin silicon membrane which is capped with thin layers of silicon oxide and silicon nitride, as schematically shown in Fig. 1(c). The starting material is a silicon-on-insulator (SOI) wafer, which consists of a silicon substrate overlaid with a 3.0 μm layer of silicon on a 1.1 μm layer of silicon dioxide. Both the SOI and the silicon substrate have crystal orientations of (100) and resistivities of 12 Ω cm, corresponding to an *n*-type doping level

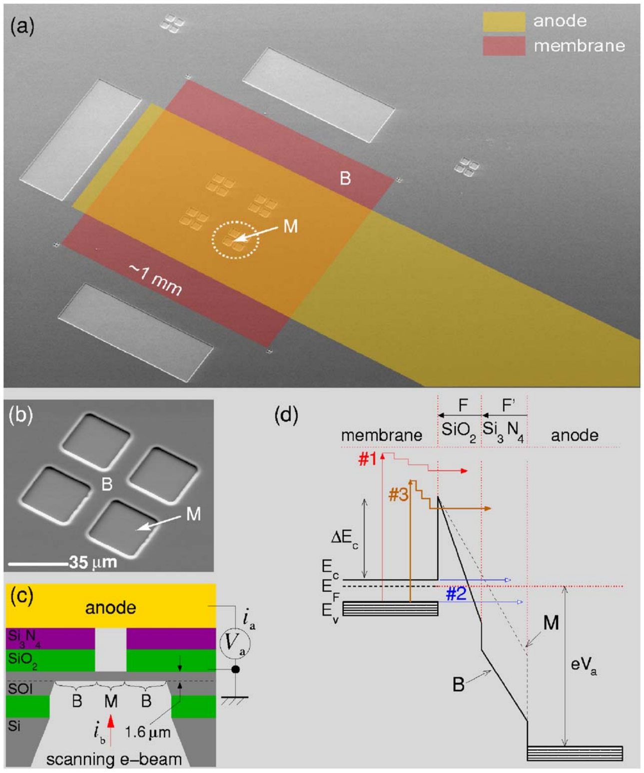

FIG. 1. (Color online) (a) A SEM image of the device. (b) A closer view of four silicon membranes (M) comparing to triple-layer membrane (B). (c) A schematic drawing of the cross section and the measurement setup. (d) Energy band diagram (not to scale, also the band bending of silicon is not shown). Note the different tunnel barriers for membranes M and B.

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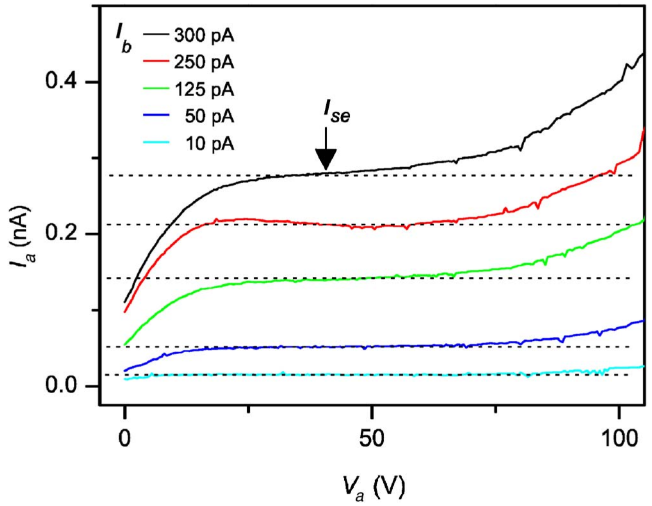

FIG. 2. (Color online) I_a-V_a characteristics reveals conventional SEE when $V_a \lesssim 50$ V. The electron beam is scanned over an area of 320×320 μm^2 covering 16 M-type membranes ($E_p = 30$ keV).

of 3×10^{14} cm^{-3}. The Fermi level is about 0.3 eV below the bottom of the conduction band at room temperature. The 3.0 μm silicon layer of the SOI is thinned by thermal oxidation to form a 1.0 μm silicon dioxide layer. In a low pressure chemical vapor deposition process, the whole wafer is then capped with a thin layer of silicon nitride (900 nm), forming a SOI/SiO_2/Si_3N_4 triple layer on top of the original silicon oxide. Sixteen square windows are formed from this triple layer by optical lithography and reactive ion etching through the oxide and nitride layers. A top view of the device is shown in the scanning electron micrograph in Fig. 1(a), where 16 square windows are patterned into four 2×2 arrays. Finally, a square (1 mm^2) membrane of the triple layer and 16 silicon membranes are formed in a sequence of wet chemical etching processes performed in a window defined on the backside of the substrate. These etching processes include (1) anisotropic etching of the silicon substrate using potassium hydroxide (KOH) solution, (2) removal of the silicon oxide between the SOI and silicon substrate, and (3) thinning down the SOI layer further to 1.6 μm using anisotropic etching of silicon in KOH solution. In Fig. 1(a), the whole triple-layer membrane is seen as a red square and in the center are 16 silicon membranes. A closer view of four of the silicon membranes is shown in Fig. 1(b). Thus two distinct membrane types are fabricated on the same device: a pure silicon membrane (M) and a triple-layer membrane (B). Each M-type membrane has a dimension of 35×35 μm^2, which is only 2% of the area of the B-type membrane.

We used a modified SEM to conduct the experiments (vacuum of $p \approx 10^{-6}$ mbar): the configuration is sketched in Fig. 1(c), where the sample is clamped in a holder while the electron-beam is scanned over the backside of the membranes. The injected electrons possess energies in the range of $E_p = 1-30$ keV. The membranes are connected to ground to avoid charging due to the release of electrons. A metallic anode is placed on top of the membrane, covering the gold-color area, as shown in Fig. 1(a). This electrode provides the extraction or retarding voltage (V_a) for electrons emitted from the membranes. By controlling the anode voltage while monitoring the anode current I_a, SEE ($E \lesssim 50$ eV) can be differentiated from electrons transmitted directly through the membrane ($50 \text{ eV} < E \leq E_p$). As will be shown below, a further increase in the anode voltage induces FE from the membrane.

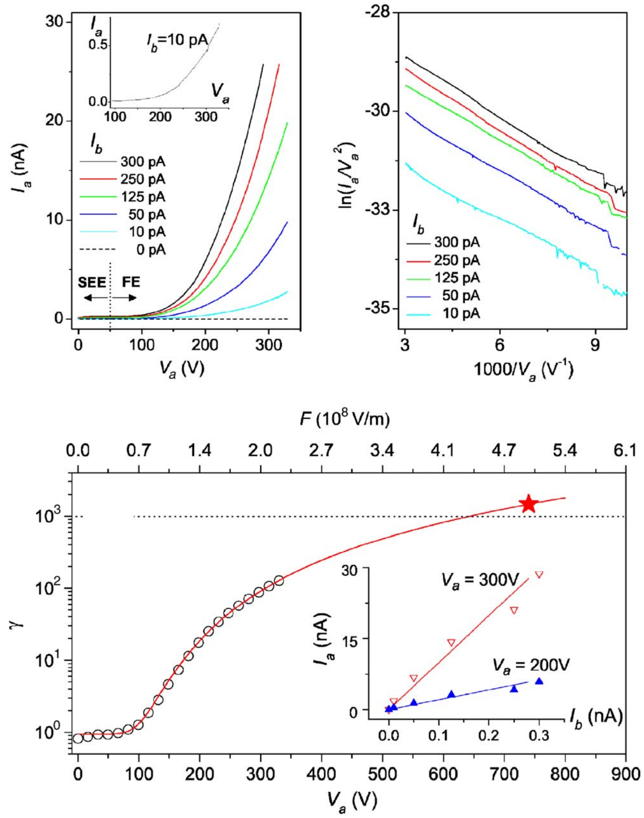

FIG. 3. (Color online) (a) Extended I_a-V_a characteristics with the anode voltage up to 350 V. Other conditions are the same as that shown in Fig. 2. The inset displays electron multiplication from an M-type membrane only. (b) The same data shown in (a) presented in a typical FN plot. (c) The total electron yield vs the anode voltage, revealing a gain of two orders of magnitude after the transition from SEE to FE. The inset shows the linear relationship between I_a and I_b at two different anode voltages.

An energy band diagram of the membrane structure is shown schematically in Fig. 1(d). The dielectric layers enhance the electric field at the surface of the SOI layer. The potential barrier for electron emission in area B is determined by the conduction band offset between silicon oxide and silicon (ΔE_c), while it is equal to the work function (Φ) of silicon for area M. When the backside of the membrane is exposed to an electron beam, SEE can be easily probed by the anode, as shown in Fig. 2. This is indicated by process 1 shown in the energy diagram in Fig. 1(d). Due to the thinness of the membrane which allows direct electron transmission, the anode already draws a finite current even at a negative bias.[1,10] The increase of V_a up to +50 V allows for a complete collection of both transmitted and true SEs, which produces a plateau in the $I_a - V_a$ curve, as shown in Fig. 2. The height of this plateau normalized by the incident beam current I_b defines the conventional electron yield from SEE $\gamma_{se} = I_{se}/I_b$, which was found to be about 0.95.

Without electron-beam excitation on the backside of the membranes, electrons in the conduction and valence bands can be emitted through FE, shown as process 2 in Fig. 1(d). Without injected electrons our device did not show a measurable FE current, even when an anode voltage of up to 350 V is applied [see the black dashed curve shown in Fig. 3(a)]. This is not too surprising since at $V_a = +350$ V, the electric fields in area B and M are only of the order of

10^8 V/m. According to the Fowler-Nordheim (FN) theory, such subthreshold electric fields do not produce a detectable electric current from an emission area of 1 mm^2. However, when the backside of the membrane with an area about 320^2 μm^2 including 16 M-type membranes is exposed to an electron beam, the anode current is significantly increased, as shown in Fig. 3(a). The electron beam has an energy of E_p =30 keV and a beam current as indicated. A similar nonlinear curve is also seen in the inset of Fig. 3(a), where the electron beam is fixed on a M-type membrane, i.e., without any dielectric layer. This suggests an emission mechanism different from the Malter effect[6] and the other known effects[7,8] which all rely on a thin layer of oxide deposited on the emitter.

The behavior of electron emission for V_a above 100 V is further examined along the FN characteristic: $\ln(I_a/V_a^2)-1/V_a$, as shown in Fig. 3(b). The straight lines over a large range of bias voltage strongly support that emission from the membranes is governed by FN tunneling: $I_a=I_{se}+I_{fe}=\gamma_{se}I_b+AV_a^2\exp(-B/V_a)$, where I_{se} stands for the conventional SEE which saturates around $V_a=50$ V (see Fig. 2), while the second term is the standard FN field emission current [A and B are material dependent constants with $B=(512\pm 31)$ V^{-1}]. Most importantly, we found that coefficient A is proportional to the incident electron-beam intensity: $A=A'I_b=(5.1\times 10^{-3}\ \text{V}^{-2})I_b$.

The total yield can now be expressed as $\gamma=I_a/I_b=\gamma_{se}+\gamma_{fe}=\gamma_{se}+A'V_a^2\exp(-B/V_a)$, which can be continuously tuned by the anode voltage. As shown in Fig. 3(c), a yield of 200 is achieved by strong FE at a bias of 350 V. Below 100 V, the yield is reduced to 0.95, which is determined by conventional SEE. The solid curve shown in Fig. 3(c) is a fit with $A'=(5.2\times 10^{-3})$ V^{-2} and $B=492$ V^{-1}, which traces γ perfectly. In the inset of Fig. 3(c) plots are represented for constant yields. Here we fixed the anode voltage and varied the electron-beam current (1–300 pA).

The above results reveal that electrons in a thin silicon membrane can be generated and liberated by the combined action of primary electrons (PEs) and an external electric field. In other words, the external subthreshold electric field induces field emission of those electrons excited by the primaries, which would otherwise remain undetected. Unlike the Malter effect, a dielectric layer on the surface of the membrane is not a must in our experiments and no self-sustained emission was observed after the scanning electron beam is turned off.[9]

The main pathway for this subthreshold field emission is illustrated as process 3 shown in the band structures of Fig. 1(d). The corresponding portion of the emission current should follow $I_{fe}\propto\int_{E_c}^{E_c+\Delta E_c}N(E)T(E,V_a)dE$, where $N(E)$ is the number of electrons excited to the energy between E and $E+dE$, and $T(E,V_a)$ is the tunneling probability. The spectrum of possible electron excitations in the thin silicon membrane by the PEs should be a continuum, starting from the bottom of the conduction band to the energy level of PEs. Electrons at the membrane surface with an energy above the tunnel barrier are true SEs since they are free to escape from the membrane. However, there are many more electrons excited with their energy below the barrier. Notably, electrons with an energy close to the top of the barrier will have a tunneling probability as high as $10^{-2}-10^{-1}$.

According to this model, a yield as high as 1000 could be realized at $V_a\approx 650$ V or equivalently $F\approx 4.4\times 10^8$ V/m, which is still below the dielectric breakdown field of silicon dioxide [$\sim 5\times 10^8$ V/m, marked by ★ in Fig. 3(c)]. However, similar oxide layers in other experiments showed breakdown at bias voltages ranging from 500 to 800 V. Since the experiment reported here was conducted by applying a prolonged high electric field and a continuously scanning electron beam which induces a high-current-density emission (~ 1 A/cm^2), we kept the bias below 400 V to avoid possible breakdown of the oxide layer. By introducing nanopillars as electron emitters onto thin membranes, we should be able to achieve an even higher yield and observe a transition from stimulated subthreshold FE to intrinsic FE.[10,11]

Apart from applications in transmission-type electron multipliers,[12] this effect also allows for determination of the excitation spectrum, producing, for example, phonons and plasmons, both of which may have an energy below the tunnel barrier and are not detectable by conventional SEE. Electron emission assisted by these quasiparticles would be valuable for developing particle/radiation detectors with ultrahigh sensitivity and low dark current.

In conclusion we have demonstrated enhancement of electron multiplication of at least two orders of magnitude in a silicon membrane device. The experimental results suggest that this field-dependent multiplication does not require a dielectric layer on the membrane as found in Malter's experiment. The multiplication is simply realized by subthreshold Fowler-Nordheim field emission. The device architecture demonstrated allows for an easy realization of stacked electron and other particle detectors and for probing electronic, photonic, or phononic excitations of thin semiconductor membranes.

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