A Cascade Electron Source Based on Series Horizontal Tunneling Junctions

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Abstract—On-chip tunneling electron sources have wide potential applications in miniature vacuum electronic devices, and emission efficiency is one of their performance benchmarks. A cascade electron source (CES) based on series metal–insulator–metal horizontal tunneling junctions (HTJs) is proposed, where free electrons are additively extracted from each tunneling junction. A CES with \( n \) HTJs shows a theoretical emission efficiency of approximately \( \eta(n) = 1 - (1 - \eta_0)^n \), with \( \eta_0 \) being the efficiency of a single tunneling junction. Experimentally, a CES with three Si–SiO\(_2–\)Si tunneling junctions is demonstrated, achieving an emission efficiency of as high as 47.6%. This work provides a new way of realizing highly efficient on-chip tunneling electron sources.

Index Terms—Cascade, electron source, horizontal tunneling junction (HTJ), on-chip.

I. INTRODUCTION

Electron sources fabricated on a chip have attracted continuous interest over a long time due to their promising applications in miniature vacuum electronic devices and systems [1]–[6]. Compared with widely studied field emission sources based on tip arrays [6], tunneling electron sources based on metal–insulator–metal (MIM) or metal–oxide–semiconductor (MOS) structures show higher potential for on-chip applications for the benefits of lower operating voltage, lower operating vacuum, and easier fabrication [1], [4]. Electron emission from these electron sources is attributed to the escape of hot electrons generated in electrically biased MIM/MOS structures. Emission efficiency, which is defined as the ratio of electron emission current to the conduction current of MIM/MOS structures, is, therefore, a benchmark for the electron source performances. However, the efficiency is typically less than 1% for several decades because of the drastic energy dissipation of hot electrons across the top metal layer. Recently, the emission efficiency has been successfully boosted to over 10% through several different ways [1], [4], [7]. By using graphene as the top layer of a MOS structure to suppress the hot electron dissipation, an emission efficiency of up to 32.1% has been reported [4].

Recently, we proposed a high-efficiency electron source based on a horizontal tunneling junction (HTJ), where an insulator nanogap is horizontally sandwiched between two thin conducting films on an insulating substrate [8]. It shows a theoretical emission efficiency of up to 21.0%–25.9% and an experimental value of 16.6% by using a Si–SiO\(_2–\)Si HTJ in electroformed silicon oxide [7]. In contrast with conventional tunneling electron sources with vertically stacked MIM or MOS structure where electrons are emitted from the surface of the topmost layer [1], [4], the unique architecture of HTJ enables lateral electron extraction from MIM or MOS structure. This makes it possible to additively extract free electrons from series HTJ in a cascade way.

Here, we propose a cascade tunneling electron source consisting of series HTJs and analyze its emission efficiency in theory. Based on three Si–SiO\(_2–\)Si HTJs in series, a cascade tunneling electron source is experimentally realized, and emission efficiency of up to 47.6% is demonstrated.

II. DEVICE STRUCTURE AND WORKING PRINCIPLES

The schematic of a cascade electron source (CES) is shown in Fig. 1(a), where several (three in the diagram) MIM HTJs are connected in series on an insulating substrate. Each HTJ consists of a thin insulator nanogap horizontally connected between two thin conducting films. The thickness \( t \) of the insulator nanogap and conducting film is set to less than the mean free path of inelastic scattering. When a bias voltage larger than \( \phi/e \) (\( \phi \) is the work function of conducting film and \( e \) is the elementary charge) is applied to such an HTJ, electrons tunnel from low-potential conducting film to the insulator nanogap. Some of them are then accelerated to above the vacuum level \( E_0 \) by the electric field in the insulator [see Fig. 1(b)] and escape laterally from the MIM junction [7]. The predicted efficiency of such an HTJ reaches as high as 25.9% [8].

When a bias voltage is applied on the two outmost electrodes of this CES, electron emission from all HTJs can take place simultaneously, and emission current from each HTJ is additive due to the lateral electron extraction [see Fig. 1(b)]. Assuming the same emission efficiency of \( \eta_0 \) for all HTJs, we get the conduction current and emission current of the \( i \)th HTJ as \( I_c = I_c^0(1 - \eta_0)^{i-1} \) and \( I_e = I_c^0\eta_0 = I_c^0(1 - \eta_0)^{i-1}\eta_0 \).
The rupture of conducting filament results in a Si–SiO$_x$–Si HTJ in the shallow surface of the substrate, which was thought to be responsible for electron emission from silicon oxide electron-emitting diodes [7]. Conduction current of a Si–SiO$_x$–Si HTJ at a bias voltage of $V$ can be described by the Fowler–Nordheim law [10]

$$I(E) = A \frac{e^3 E^2}{8 \pi \hbar \gamma} \exp \left( \frac{-8 \pi (2m^*)^{1/2} \chi^{3/2}}{3 \hbar e E} \right)$$  (3)

where $A$ is the cross section area of an HTJ, $h$ is the Planck’s constant, $\gamma$ is the potential barrier at the Si–SiO$_x$ interface, $m^*$ is the effective mass of SiO$_x$, and $E = V/d$ is the strength of the electric field, with $d$ being the width of an HTJ. According to the method in our previous work [8], the curve of $\eta(E)$ together with that of $I(E)$ is calculated, as shown in Fig. 2(a), for a Si–SiO$_x$–Si HTJ with the parameter values of $A = 4 \text{ nm} \times 10 \text{ nm}$, $\gamma = 1.0 \text{ eV}$, $m^* = 0.42m_0$, and $d = 20 \text{ nm}$, where $m_0$ is the rest mass of an electron. To simplify the analysis, the effect of impurities and surface defects, which strongly depends on materials and fabrication and can be minimized during the fabrication process, is neglected for estimating the ideal performance of the CES.

Emission efficiency of a CES with $n$ identical Si–SiO$_x$–Si HTJs can then be simulated based on the relations of $\eta(E)$ and $I(E)$ in Fig. 2(a). Despite the same geometric structure, each HTJ in the CES will show a different conduction current due to the extraction of emission current from the circuit and, thus, different voltage drops and emission efficiencies for each HTJ. If the voltage drops across conducting filaments are neglected, self-consistent equations for a CES with $n$ identical Si–SiO$_x$–Si HTJs can be obtained

$$V = \sum_{i=1}^{n} V^i$$

$$E^i = \frac{V^i}{d}, \quad i = 1, 2, \ldots, n$$

$$I^i = I^i(E^i), \quad i = 1, 2, \ldots, n$$

$$I^i_{+1} = I^i_c(1 - \eta(E^i)), \quad i = 1, 2, \ldots, n$$

$$\eta = \frac{I^i_{+1}}{I^i_c}$$

where $V$ is the voltage applied to the CES, $V^i$ and $E^i$ are the voltage drop and the electric field strength of the $i$th HTJ, $I^i_{+1}$ is conduction current going out of CES, and $\eta(E^i)$ and $I(E^i)$ are the functions plotted in Fig. 2(a). Equations (1) and (5) are derived from Kirchhoff’s laws, and (4) and (6) are derived directly from the definition of emission efficiency. There are $3n + 3$ equations and $3n + 3$ unknown variables ($V_1, E_1, I_1, I_{+1}^1, I_c$, and $\eta$), so the equations can be numerically solved with unique solutions for a given $V$ and $d$.

Fig. 2(b) shows the calculated $\eta$ of a CES with respect to $n$ at different $E^1$ by (4) (solid lines). It can be seen that $\eta$ increases with $n$ for a fixed $E^1$. When $E^1 = 1.5 \text{ V/mm}$, $\eta$ has the value of 21.0%, 37.4%, 50.3%, and 60.5%, respectively, for $n = 1$–4. For a fixed $n$, $\eta$ also increases with $E^1$. A CES with four HTJs has emission efficiencies of 49.0%, 54.8%, and 60.5%, respectively, for $E^1 = 1.0, 1.2,$ and
1.5 V/nm. We also plot η with respect to n in Fig. 2(b) by taking \( \eta_0 = \eta(E^1) \) into (2) (dotted lines). Self-consistently calculated efficiencies from (4) are slightly lower (<0.5%) than those from (2). Therefore, (2) can give η of a CES with identical HTJs in a good approximation. The reason for the high consistency is attributed to the exponential dependence of conduction current on the strength of the electric field in Fowler–Nordheim equation [see Fig. 2(a)], which means that a considerable variation of \( I_i \) resulted from electron emission will not bring much variation in the strength of the electric field \( E_i \) or emission efficiency \( \eta(E) \) of neighboring HTJs. Fig. 2(c) shows voltage drops (\( V^i \)) and emission efficiencies \( \eta(E^i) \) of each HTJ in a CES with \( n = 4 \). The quite similar emission efficiency for the four HTJs further confirms that it is reasonable to assume the same emission efficiency, as in obtaining (2). Fig. 2(d) shows the dependence of \( \eta \) on \( V \). \( \eta \) increases with \( V \) until reaching a maximum value when \( E^i \) increases to 1.5 V/nm, the maximum electric field strength that silicon oxide can withstand [11]. It can be seen that the maximum achievable \( \eta \) of a CES increases with \( n \).

### IV. Experimental Demonstration

A CES with three Si–SiOₓ–Si HTJs is experimentally demonstrated. Fig. 3(a) shows a schematic of a CES with three Si–SiOₓ–Si HTJs and its measurement setup. A scanning electron microscopy (SEM) image of a CES before the measurement is shown in Fig. 3(b), where three Au/Ti nanowires (Au/Ti =10 nm/5 nm, 2 μm in length, and 200 nm in width) are fabricated in series on a SiO₂ substrate (SiO₂/Si = 300 nm/525 μm) with each Au/Ti nanowire connected between two electrodes (Au/Ti =45 nm/5 nm). Compared with previous work using graphene or carbon nanotube as the electrodes [7], Au/Ti nanowire is easier for fabrication in an extensible way and more compatible with conventional semiconductor technology, which is beneficial for mass production. Emission current measurement is carried out in a JANIS probe station with a vacuum level of \( 10^{-3} \text{--} 10^{-2} \) Pa. A tungsten probe around 200 μm above the device with a bias of 210 V is used to collect emission current. The electron emission performances and electrical transport properties are measured with a KEITHLEY 4200 semiconductor system in direct current mode. It should be noted that some electrons can be collected by the electrode of the HTJ with higher electric potential; not all the emitted electrons are collected by the collector. Thus, the collecting efficiency \( \eta_c \) should be multiplied by simulated efficiency to predict the measured emission efficiency. The empirical collecting efficiency of the measurement setup is in the range of 75%--99%, depending on the location and voltage of the collector electrode. The predicted measured emission efficiency, accordingly, should be 15.75%--20.79% for a single HTJ and 37.73%--49.80% for a CES with \( n = 3 \).

To form a Si–SiOₓ–Si HTJ, a Ti/Au nanowire is first broken by Joule heating under a low voltage of around 1.5 V to form a nanogap [see Fig. 3(b), inset], and then, SiO₂ under the broken gap is electroformed [9]. The statistical estimate of the length of nanogap is 89.3 nm ± 56.5 nm according to 11 devices, with a variation range of 15–178 nm. Such a large variation of the dimensions of nanogaps between Ti/Au nanowires is tolerable because electron emission does not come from the larger nanogap between Ti/Au nanowires but from the smaller nanogap between broken Si conducting filaments. The dimensions of larger nanogap between Ti/Au nanowires only affect the threshold voltage needed in the electroforming process to form the conducting filament. Furthermore, uniform nanogaps between Ti/Au nanowires can be fabricated by employing electron-beam lithography and reactive ion etching. Electroformed SiO₂ exhibits a unipolar resistive switching behavior [see Fig. 3(c)], which is attributed to the reversible rupture and connection of Si conducting filament formed in shallow surface of the substrate [7], [9]. A Si–SiOₓ–Si HTJ is, therefore, formed in the nanogap when a conducting filament is ruptured in the high-resistance state [see Fig. 3(a)]. A Si–SiOₓ–Si HTJ can generate considerable electron emission [7], as shown in Fig. 3(c). Emission current (orange curve) of a Si–SiO₂–Si HTJ rises with the increasing bias voltage until reaching 2.57 μA, and the maximum emission efficiency reaches 15.9% (2.57 μA/16.2 μA), which is
comparable with that reported in [7] and in agreement with the predicted efficiency.

After a Si–SiO$_x$–Si HTJ is formed between each pair of neighboring electrodes, a CES with three Si–SiO$_x$–Si HTJs is prepared. Its electron emission is driven by applying a bias voltage to the two outmost electrodes. Since the generation and rupture of conducting filaments are drastic redox processes, the local structure of HTJs in the CES changes constantly, bringing large fluctuations to the curves of conduction current and emission current [see Fig. 3(d)]. An emission current of 5.0 μA is achieved at 57.1 V for a CES with three Si–SiO$_x$–Si HTJs, corresponding to an emission efficiency of as high as 47.6% (5.0 μA/10.5 μA) [see Fig. 3(d)]. The efficiency is much higher than that (32.1%) of the previous graphene–oxide–semiconductor tunneling electron source, which uses atomic graphene as the top electrode to minimize the dissipation of hot electrons [4]. It agrees well with the theoretical estimate of 37.73%–49.80% ($\eta_0 = 21.0\%$, $E^1 = 1.5$ V/nm, $n = 3$, and 75% $<\eta_e < 99\%$) for a CES with three HTJs.

An SEM image of the CES after tens of emission current measurements is shown in Fig. 3(e), where some contaminations can be clearly seen between each neighboring electrodes. Electron-beam-induced deposition of amorphous carbon is a commonly seen phenomenon in instruments with free-electron beams when it does not operate in a high vacuum [12]. Since the device before the measurement is clean, as shown in Fig. 3(b), the contamination is thought to be amorphous carbon deposition arising from the radiolysis of residual hydrocarbon molecules by free electrons emitted from HTJs. The presence of amorphous carbon between each pair of neighboring electrodes [see Fig. 3(e)] provides solid evidence that electrons are emitted from the three Si–SiO$_x$–Si HTJs in the CES at the same time. Though the three HTJs may not show identical structures as in the theoretical model, which is speculated from quite a different amount of amorphous contamination around them, our measured efficiency of as high as 47.6% unambiguously indicates that CESs provide an effective way of boosting emission efficiency.

The stability of the CES itself is still not satisfactory until now. The emission process is along with an electroformed structure, which brings fluctuation to both the conduction and emission current curves. However, this fluctuation can be eliminated with current-controlled circuits, as in the cases with other on-chip electron emitters [13]. Even though it is not stable, the high efficiency of a CES is repeatable. We have performed over 30 cycles of measurement on the CES in Fig. 3(b), and Fig. 3(d) shows the result of the 23rd and 31st measurements of the same device. We can see that both the two measurements show emission efficiencies over 45%, without showing obvious degradation.

To achieve a large enough current for practical application, more HTJs can be fabricated in series in a single CES. In addition, many CESs can be integrated parallelly as a CES emitting array to get a larger emission current.

V. Conclusion

A CES based on series HTJs is proposed for the first time as a new form of on-chip electron sources. Through both theoretical simulation and experimental demonstration, CES is proved to be an effective way to further improve the emission efficiency of tunneling electron sources. Based on Si–SiO$_x$–Si HTJs formed in electroformed SiO$_2$, a CES with three HTJs is demonstrated in experiments, and emission efficiency of as high as 47.6% has been achieved. Our work provides a new way of realizing highly efficient on-chip electron sources.

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