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Photon Emission by Silicon-Based Memristors

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Abstract *We introduce a new category of nanoscale photon sources based on memristors with silicon-based switching matrices. These novel photon sources exhibit light emission during the switching of their resistive state. The photon emission is attributed to the creation and excitation of silicon nanoclusters. ©2022 The Author(s)*

Introduction

The introduction of a compact CMOS compatible on-chip photon source is a major challenge to this very day. Despite steadily increasing research interest in this field [1], the significant size mismatch between on-chip photon sources and the nanoscale electronic components still greatly hinders their large-scale co-integration [2–4]. This co-integration would be highly desired as on-chip photonics, with its centerpiece the photon source, offers a largely superior bandwidth and lower latency at a lower power dissipation compared to the electronic counterparts [3–5]. As such, incorporating photonics into the CMOS technology would resolve many challenges on the current path of digital electronics towards atomic scale feature sizes and would herald in a next generation of computing [3,5–7].

The currently most promising on-chip photon sources for the near future include lasers based on III-V materials, Germanium, and its alloys. In spite of their performance, these solutions suffer from inherently large feature sizes in the order of micrometers [2,8,9]. At smaller physical dimensions, new photon sources have emerged such as quantum dot based light sources [10–12] and inelastic tunnelling emitters [13–15]. However, whereas electrical injection of carriers in quantum dots is still fundamentally difficult [9], tunnelling emitters require an extremely thin tunnelling barrier that requires advanced nanofabrication [15] or stochastic arrangement [13] limiting their yield and their applicability as on-chip photon sources.

Recently we introduced a novel atomic scale photon source based on a memristor with an oxygen-rich SiO_x (x<2) switching matrix offering both the required nanoscale dimensions as well as a straightforward, scalable and CMOS compatible fabrication process [16]. It exhibits electroluminescence during the switching of its resistive state.

In this work we demonstrate that this memristive photon emission effect is not limited to oxygen-rich SiO_x but also occurs in Si. We propose that this functionality can be exploited in many Si-based switching matrices by introducing a photon emission mechanism for such Si-based memristive photon sources. As Si-based materials are amongst the most commonly used switching matrices for this memristor technology [17,18], photonic functionalities could be employed within existing memristor applications which would extend their already imposing capabilities in neuromorphic computing and memory technologies [19,20]. Furthermore, this novel category of nanoscale photon sources - even though showing weak emission in these first experiments - has a great potential for large-scale co-integration with digital electronics. This would allow to make use of the advantages of the CMOS technology, photonics and the memristor technology on a single chip.

Device Structure and Operating Principle

The device platform of the memristive photon source is depicted in Fig. 1(a). It consists of a silver and a platinum electrode with amorphous Si (a-Si) or amorphous, oxygen-rich SiO_x (x>2) as switching matrix, fabricated on a glass coverslip. The electrode tips are shaped to form an optical antenna enabling enhanced radiation efficiencies at the emission wavelength. Applying a positive voltage between the silver and platinum electrode causes these devices to switch from a high to a low resistance state by forming a metallic filament as depicted in Fig. 1(b). Such cells are known as electrochemical metallization (ECM)-type memristors [17,18].

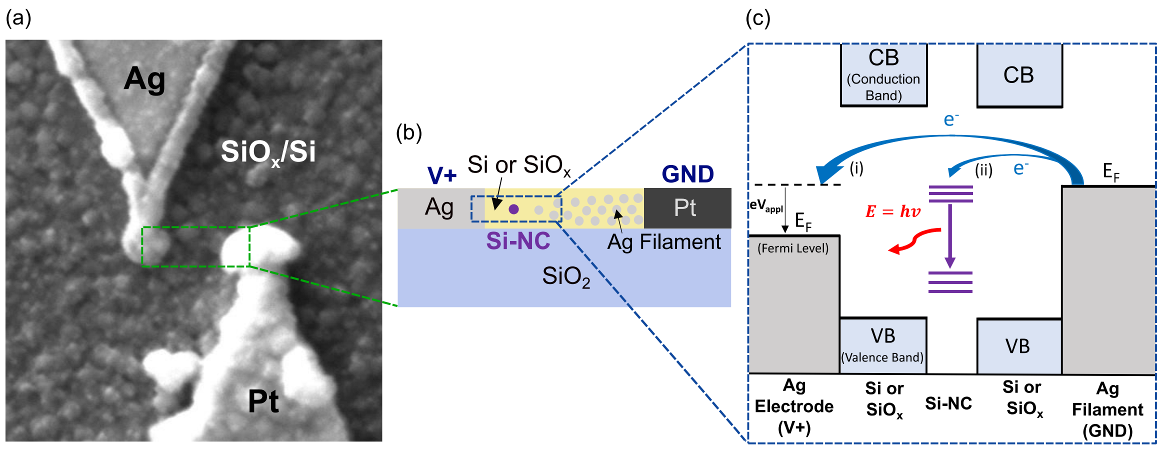

Fig. 1: Device structure and operating principle. (a) SEM picture of the device structure. The photon source consists of structured Ag and Pt electrodes within either an amorphous Si (a-Si) or oxygen-rich, amorphous SiO_x (a-SiO_x) switching matrix. (b) Switching mechanism and creation of defects. Upon applying a voltage to the device, a metallic filament consisting of Ag atoms grows from the Pt towards the Ag electrode. During this process, silicon nanocluster-type defects (Si-NC) are introduced in the switching matrix. (c) Photon emission mechanism. Due to the growing filament, electron tunneling increases drastically. These electrons can either tunnel to the Ag electrode (i) or excite Si-NC defects (ii). In the latter case, radiative recombination occurs, and photons are emitted.

The operating principle of photon emission is based on the creation and excitation of luminescent sites within the switching matrix. More precisely, in a process concurrent with the switching to a low resistance, the applied voltage and the filament formation cause local alterations of the switching matrix between the electrodes (details see *Analysis of Si-NC related photon emission*). This creates luminescent silicon nanocluster-type defects (Si-NC), shown in Fig. 1(b). As illustrated in Fig. 1(c), these created Si-NC can be excited by individual tunnelling electrons (i) that are part of the total tunnelling current (ii). This causes light emission by radiative recombination.

Measurements

In Fig. 2(a) and (b), time-resolved electro-optical measurements of devices with an a-Si and a-SiO_x switching matrix are shown, respectively. The measurements were performed by applying a voltage pulse (black solid line) while concurrently capturing the emitted photons with an avalanche photodiode (APD), see red line. The emission of photons for both switching matrices is clearly a transient phenomenon occurring at the instance when the devices switch from their high to their low resistance state (blue solid line) or in other words at the onset of a forming metallic filament. The number of detected photons in the case of a-Si is lower. This is likely explained by the fact that the optical environment during the photon emission process is drastically different for a-Si compared to a-SiO_x. Particularly, silicon introduces absorption at the wavelength of emission and causes a reflection due to the refractive index mismatch with the glass substrate, both of which are causing a lower collection efficiency.

In Fig. 2(c), the normalized spectra of two devices with either an a-Si or a-SiO_x switching matrix are shown. The spectra were measured by applying a series of voltage pulses to the device, thereby triggering many switching and thus photon emission events. The emission spectra of the two device types are broadband and largely overlapping at smaller wavelengths with a peak around 740 nm observed in both cases. The spectrum of the a-Si additionally exhibits a main peak at 840 nm. These characteristics of the two spectra are attributed to the peculiarities of silicon nanocluster-related photon emission. Not only is the local optical environment of each cluster slightly different (inhomogeneous broadening) but also the size and especially the interface of the nanoclusters are known to greatly influence the emission wavelength (homogeneous broadening) [21,22]. As a result, we expect many sub-variants of silicon nanoclusters with varying emission wavelengths that are created and excited during the numerous switching events, causing broadband emission. As the conditions of Si-NC formation in the two switching matrices are distinct, a different relative abundance of sub-variants is expected which would explain the shift of the main peak in the two spectra.

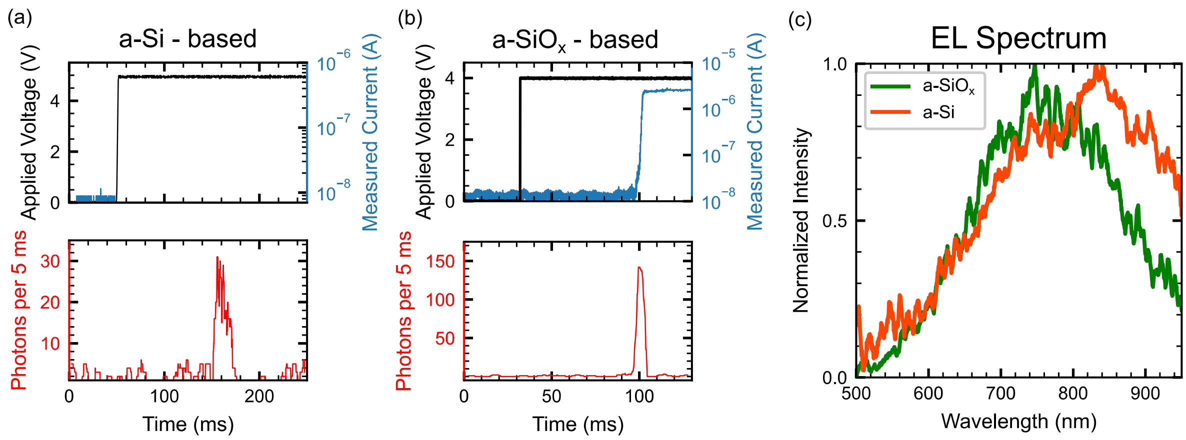

Fig. 2: Electro-optical measurements of the memristive photon sources with a-Si and a-SiO$_x$ switching matrices. (a) and (b) Time-resolved measurements with an a-Si (a) and an a-SiO$_x$ matrix (b). The measurements clearly show a transient photon emission effect that occurs during the switching to a lower resistance state. In both measurements, photons are also apparent before and after the switching. These detection events were attributed to the dark counts of the avalanche photodiode (APD). (c) Electroluminescence spectrum measurements for both switching matrices. The spectra are broadband and largely overlap, indicating the same origin of photon emission. The differences between the two spectra are attributed to different relative contributions of Si-NC variants occurring in the respective switching matrices.

Analysis of Si-NC related photon emission

The formation of the luminescent silicon nanoclusters slightly differs for the two switching matrices. As we previously reported [16], in oxygen-rich SiOx, oxygen vacancy creation and aggregation occurs in a similar way as in oxide-based RAM (OxRAM) memristors [23]. The aggregation of these oxygen vacancies forms locally Si-rich regions with silicon nanoclusters (Si-NC), which are known to produce electroluminescence (EL) and photoluminescence (PL) at the wavelengths matching the light emission reported in Fig. 2(c).

In the case of pure silicon, the occurrence of silicon nanoclusters is also well established. In fact, the first room temperature PL from silicon nanoclusters was observed in porous Si. It was attributed to the quantum confinement caused by the etching of the silicon to produce the porous structure [22]. As for a-Si there is no quantum confinement as there is no separation of such nanoclusters from the bulk. However, there are numerous reports of resistive switching in a-Si which was attributed to local alterations of the silicon that form a filament of higher conductivity upon application of a bias [24–26]. We propose that this effect of bias-induced alteration of the a-Si leads to the segregation of luminescent Si-NCs. More precisely, Si-defects such as Si-dangling bonds are known to form the (preliminary) interface of silicon nanoclusters, thus separating them from the bulk [21]. These dangling bonds are the dominant intrinsic defects in a-Si and due to their low formation energy they can be created by a low electrical bias [27–29].

In conclusion, in a process concurrent with the switching of the memristive photon source, both oxygen-rich a-SiO$_x$ and a-Si matrices see the formation of Si-NC structures that allow electrical excitation and photon emission.

This creation of localized Si-NC is not restricted to memristors with the switching matrices presented here. The occurrence as well as the creation of these clusters have been reported in silicon-rich SiO$_x$ ($x<2$) [30,31] and in SiN$_x$ [32,33]. This suggests that the presented photon emission mechanism might be occurring in many Si-based switching matrices.

Conclusion

We demonstrate a new CMOS-compatible device platform for next-generation nanoscale photon sources based on the memristor technology. Light emission is observed in both a-Si and a-SiO$_x$ with very similar emission characteristics. The photon emission was attributed to the creation and excitation of silicon nanoclusters. This effect is expected to occur in many more Si-based switching matrices which would allow to make use of the photon emission capability in many existing memristor technologies.

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