SIDEWALL SILICON CARBIDE EMITTERS FOR TERAHERTZ VACUUM ELECTRONICS

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ABSTRACT

This paper describes a functional sidewall emitter for future terahertz vacuum electronics. The thermionic emitter is formed by a 1 μm thick film of low-stress n-type polycrystalline silicon carbide (SiC), conformally deposited by LPCVD onto high aspect ratio silicon trench sidewalls and subsequently released. The free-standing emitter is resistively heated. We demonstrate lateral thermionic currents of 100 μA , measured on an integrated collector across a high aspect ratio vacuum gap, for 300mW heating power.

INTRODUCTION

The frequency band from 250 GHz to 2.5 THz is rich in potential applications, but suffers from a lack of efficient sources. This “THz gap” arises from the sharp decrease in the efficiency of solid-state electronic amplifiers at frequencies above 100 GHz and the unavailability of compact, uncooled optical sources for wavelengths longer than the infrared [1]. A micro-fabricated Barkhausen-Kurz ($\mu\text{-BK}$) oscillator has been previously proposed as a promising candidate source [2,3]. The $\mu\text{-BK}$ oscillator has significant advantages over other vacuum electronic devices, including its capability of operating at harmonics of the electron orbital frequency with large admittances [4]. This paper demonstrates a functional emitter for injecting a sheet electron beam into a silicon $\mu\text{-BK}$ THz cavity (Figure 1). Our group has previously demonstrated thermionic emitters using poly-SiC films [5]; however, the need for an emitter integrated into the parabolic potential well is a major challenge. We report here a sidewall lateral emitter intended for production of an upright sheet electron beam.

Figure 1: 3D view of the $\mu\text{-BK}$ showing quadrupole electrodes surrounding the vacuum interaction region. The emitter, collector, and THz resonant cavity form the four quadrupole electrodes.

THEORY

Lateral Emission

Prior work on micro-fabricated emitters has focused on out-of-plane emission for assembly into an external device. To realize a process for terahertz integrated circuits it is desirable to fabricate the entire device on a single substrate. To enable lithographic definition of the quadrupole shaped electrodes, a novel lateral emitter producing a high aspect ratio lateral sheet beam is required. The desired electron orbit frequency limits the electric field strength inside the potential well and precludes the ready use of a field emitter array. A sidewall lateral thermionic emitter is therefore an attractive candidate for future $\mu\text{-BK}$ oscillators.

Thermionic Emission

Observation of thermionic emission predates the discovery of the electron. When a conductor is elevated in temperature a significant current of electrons with sufficient energy to escape into vacuum arises. The density of this current is given by the Richardson-Dushman equation:

$$J = A_E T_E^2 e^{-\Phi_E/kT}$$

where Φ_E is the emitter work function, T_E the emitter temperature, and A_E the materials-specific Richardson-Dushman constant. The exponential term is much smaller than unity due to Φ_E exceeding kT at temperatures below the material melting point. Thus, emission current rises rapidly with temperature.

Resistive Heating

Under the idealized assumptions of uniform constant thermal conductivity and neglecting radiation losses, the temperature profile along the length of a resistive heater will be parabolic. When a current is applied, the maximum temperature will occur at the center of the heater and is proportional to the total joule heating generated due to resistive loss:

$$\Delta T = \frac{V^2}{R_e} \frac{R_{th}}{8}$$

where V is the voltage across the heater, R_e is the electrical resistance, and R_{th} is the thermal resistance. This shows that to get maximum temperature elevation in the heater the thermal resistance should be maximized while simultaneously minimizing the electrical resistance. While the two assumptions stated above are not strictly valid at elevated temperatures, the basic temperature distribution and scaling is illustrative.

Owing to the approximately parabolic profile of temperature distribution, combined with the strong dependence on thermionic emission with temperature, the emitted electron current density will be confined to a narrow central region of the emitter. This is desirable for the formation of a confined sheet electron beam for tight coupling to a THz resonant cavity. Since thermionic emission is a surface phenomenon, a thin resistive heater film is desired to minimize required electrical heater power.

FABRICATION

Fabrication of lateral sidewall emitters starts with an SOI wafer with a 50 μm thick device layer. The device layer thickness determines both cavity depth and emitter filament height. Because of the challenges of using spin-coated photoresist for optical lithography after deep etching, a double hard mask process was used. First a 1.5 μm thick layer of silicon nitride was deposited followed by a 1.5 μm thick layer of silicon dioxide. These layers define the locations for the two critical deep reactive-ion etch (DRIE) steps.

Figure 2: Fabrication process from top left to bottom right: (1) deposit 1.5 μm LSN then 1.5 μm of LTO on SOI wafer; (2) pattern and RIE etch LSN, LTO for SiC trench definition; (3) pattern and RIE etch LTO, stopping on LSN; (4) DRIE trench to define SiC filament locations; (5) LPCVD 1 μm thick poly-SiC extremely conformal deposition; (6) blanket RIE etch poly-SiC; (7) etch LSN mask using LTO hard mask; (8) DRIE etch to define vacuum gaps and electrode isolation trenches; (9) etch remaining topside hard mask, release buried oxide, deposit bondpads using a shadow mask in an evaporator.

Figure 3: SEM showing 200nm poly-SiC film conformally lining sidewalls of a 4 μm wide and 100 μm deep DRIE etched trench in silicon. The SiC at the bottom of the trench and topside of wafer has been removed during a blanket RIE etch. A short decoration etch in XeF_2 has been performed (puckering the cleaved silicon surface) to highlight the thin SiC film.

After hard mask patterning, the first DRIE is performed stopping on a 2 μm thick buried oxide. Then, 1 μm of 10-20 m Ω -cm n-type polycrystalline SiC with an intrinsic stress of 325 MPa is deposited using LPCVD [7] to conformally coat the sidewalls of the trench. Poly-SiC was chosen because it is refractory material and because it can be deposited with extremely conformally in the LPCVD reactor. The poly-SiC is then blanket etched from the topside and trench bottoms using an anisotropic HBr/Cl_2 chemistry in a Lam TCP etcher [8]. In characterizing the process, the anisotropic reactive-ion etch was able to remove the poly-SiC material even from the bottom of 100 μm deep trenches with an aspect ratio of 25 (Figure 3).

The remaining poly-SiC layers on the trench sidewalls form the thermionic filaments. The top SiO_2 hardmask is used to reactive-ion etch the SiN hardmask layer to clear regions for the second DRIE. The poly-SiC filaments are then exposed by a silicon DRIE to define the vacuum gap/cavity. This is followed by final removal of the buried oxide using vapor HF. A shadow mask, fabricated using a silicon wafer, was used to define contacts to the poly-SiC using sputtered gold with a chrome adhesion layer.

Figure 4: SEM showing a lateral sidewall emitter with integrated collector after fabrication is completed. The transfer of scallops and vertical striations formed during the silicon DRIE into the conformally deposited poly-SiC film are clearly visible.

EXPERIMENTAL SETUP

After fabrication, individual dies were mounted on a printed circuit board and connected via wirebonds (a single device at a time). The board was placed inside a vacuum chamber with measured pressure below 10 μTorr . The device under test was connected via electrical vacuum feedthroughs to two Keithley 2400 source meter units. The filament was resistively heated by applying a negative bias voltage, V_{emitters} , to one anchor while keeping the other anchor grounded. Thermionic emission current was collected on an adjacent in-plane silicon collector positively biased at 1V (Figure 5). The negative bias on the emitter anchor ensures electrons flow efficiently to towards the positively biased adjacent collector.

Figure 5. Schematic of emission test setup inside the vacuum chamber

RESULTS

The measured resistance of the fabricated filaments ranged from 250 to 350 Ohms depending on the amount of overlap of the gold contact onto the SiC filament. The measured thermionic current data (Figure 6) fits the expected relationship between current and heater power. Thermionic emission became detectable above 100 mW emitter heating power. Over 100 μ A of collector current was measured for emitter heating power above 300 mW. As the device was kept biased at constant heater power for more than 72 hours, degradation in thermionic emission current was observed. The work function for the 3C-SiC film used was previously reported in the range 3.2-3.8 eV [5]. The device degradation over prolonged bias can be attributed to the work function increase due to the graphitization of the emitter surface. Using BaO coatings to lower the surface workfunction on SiC, a 5-6 orders of magnitude improvement in thermionic current is reported [9].

Figure 6. Measured collector current as a function of applied emitter heating power. Over 100 μ A of collector current was measured for emitter heating power above 300 mW.

At high temperatures (>1000K), the optical emissivity of polycrystalline 3C-SiC is sufficiently large to enable temperature measurements using an optical pyrometer (PYRO MicroTherm, 550-nm operating wavelength). Work is ongoing to optically measure the emitter temperature during resistive heating.

CONCLUSION

The demonstrated lateral filament is suitable for integration in a parabolic potential well formed by lithographically defined electrodes. Thermionic emission current exceeding 100 μ A was

measured for emitter heating power above 300 mW. The electron beam's negative admittance at resonance can be measured directly to guide the design of μ -BK oscillators. The demonstrated sidewall filament emitters allow the design of revolutionary vacuum electronics that combine electron emitters, coupled resonant cavities and lithographically shaped electrodes in a single substrate. This will enable a new class of efficient THz vacuum electronic integrated circuits capable of filling the "THz gap" with portable THz electronic systems.

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