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Zero-bias microwave detectors based on array of nanorectifiers coupled with a dipole antenna

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ABSTRACT

We report on zero-bias microwave detection using a large array of unipolar nanodevices, known as the self-switching diodes (SSDs). The large array was realized in a single lithography step without the need of interconnection layers, hence allowing for a simple and low-cost fabrication process. The SSD array was coupled with a narrowband dipole antenna with a resonant frequency of 890 MHz, to form a simple rectenna (rectifying antenna). The extrinsic voltage responsivity and noise-equivalent-power (NEP) of the rectenna were ~70 V/W and ~0.18 nW/Hz$^{1/2}$, respectively, measured in the far-field region at unbiased condition. Nevertheless, the estimated intrinsic voltage responsivity can achieve up to ~5 kV/W with NEP of ~2.6 pW/Hz$^{1/2}$.

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1. Introduction

In the last few decades, the development of high-frequency detection systems by means of high-speed diode rectifiers operating at zero bias has become one of the major areas of research [1–3]. Zero-bias detectors offer not only low dc power consumption since no external biasing circuit is required, but also an improvement on the signal-to-noise ratio (SNR) of the devices (i.e., high sensitivity) because they exhibit lower 1/*f* noise when compared with biased detectors. This is significantly useful especially in passive detection systems. However, the diode rectifiers must possess a strong nonlinearity behavior at zero bias in order to convert high-frequency signals into usable dc power. Among these promising zero-bias rectifiers such as Schottky barrier diode (SBD) [1], backward diode (BD) [2] and planar-doped barrier diode (PDBD) [3], here we report on a unipolar nanodevice known as the self-switching diode (SSD), first introduced by Song et al. [4].

The SSD is a unipolar two-terminal device. It has an asymmetric semiconductor nanochannel, which can be realized by tailoring the channel boundaries i.e., the two L-shaped trenches, as shown in Fig. 1(a). This yields a nonlinear current–voltage (*I*–*V*) characteristic that resembles the behavior of a standard diode [see Fig. 1(b)]. The SSDs can therefore be utilized as a signal rectifier. Unlike conventional diodes, the operation of SSD does not rely on any doped junction or Schottky barrier. The threshold voltage of the SSD is tunable, obtained by varying the channel width of the device. In this way, a virtually zero-threshold-voltage SSD-based rectifier, which operates without the need for any external biasing, can easily be achieved. Further details of the working principle of SSDs can be found elsewhere [4–6].

The SSD possesses an intrinsically low parasitic capacitance, due to the planar nature of its structure. This is the main property of SSD which enables signal rectification at higher frequency (up to terahertz) than a standard vertical diode [7]. The inherent planar structure of the SSD also allows the fabrication of a large number of the devices in a single lithography step. Interconnection layers which may introduce parasitic elements are therefore no longer required. As such, the whole fabrication process of SSDs has been made simpler, faster and at lower cost when compared with other rectifying devices such as SBDs, BDs and PDBDs. A typical high-speed SBD requires the formation of very challenging fabrication structures such as air bridges and whisker-like contact electrodes [1,8]. In the cases of BDs and PDBDs, an accurate and precise doping approach, which is complex and relatively high cost, is of paramount importance in order to produce the critical doped layers that meet the desired characteristics of the devices [2,9].

This report is a follow up of our previous work whereby the capabilities of two large SSD arrays based on InGaAs/InAlAs heterostructure operating as a zero-bias detector has been

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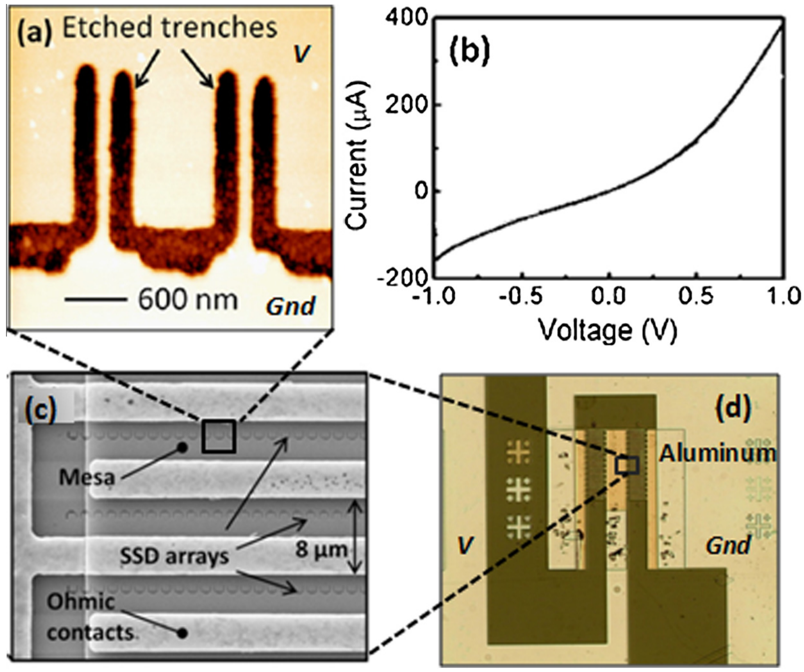

Fig. 1. (a) Atomic-force microscope image of the SSDs connected in parallel. The channel length and width were 1500 nm and 130 nm, respectively. The trench width and depth were 200 nm and 45 nm, respectively. (b) Current–voltage characteristic of the SSDs measured at room temperature. (c) Scanning electron microscope image of the SSD array fabricated within the fingers of the interdigital structure. (d) Optical image of the coplanar waveguide in which the merged SSD array was realized by thermal evaporation of aluminum.

experimentally demonstrated and characterized with coplanar waveguide measurements at frequencies up to 3 GHz [10]. However, in this work, both arrays were merged together. The combined array was coupled with a narrowband custom dipole antenna to form a simple rectenna (short-form of rectifying antenna), which was then used to receive and rectify microwave signals generated by a network analyzer and transmitted via a half-wave dipole antenna at ambient conditions. Connecting such a large number of SSDs in parallel would reduce the total resistance of the array, thus slightly improving the impedance mismatch of the rectenna. This helps to increase the amount of the microwave signal power delivered to the SSD array.

2. Device fabrication and experimental set up

The SSD array was fabricated within the fingers of an interdigital structure which was coupled to a coplanar waveguide as shown in Fig. 1(c) and (d). The SSDs were realized on an InGaAs/InAlAs heterostructure, grown onto an InP substrate (purchase from IQE Inc.). The 2-D electron gas (2-DEG) layer, where the free electrons were confined in the InGaAs quantum well, was located 25 nm below the surface of the substrate. The room-temperature electron concentration and mobility, as determined by Hall measurements, were 1.3×10^{12} cm^{-2} and 10,400 cm^2/Vs, respectively.

The fabrication began with the construction of mesa structures by a $H_3PO_4/H_2O_2/H_2O$-based etch solution. The thermal evaporation of a 50 nm of Au/Ge/Ni alloy, followed by 200 nm of Au, was conducted to form ohmic contacts on the mesas. The materials were annealed at 390 °C. The SSD array was then fabricated using electron-beam lithography and wet-chemical etching with a $Br_2/HBr/HNO_3/H_2O$-based solution. The channels of SSDs were ~130 nm wide and ~1500 nm long, and the trenches width and depth were ~200 nm and ~45 nm, respectively, as determined by the atomic-force microscope image [see Fig. 1(a)]. A relatively wide channel was intentionally designed in order to provide a zero-threshold rectifier.

The SSD arrays on the left-hand and right-hand sides of the interdigital structure were merged together by thermal evaporation of a 100 nm of Al to form a large array of approximately 2000 SSDs connected in parallel [see Fig. 1(d)]. The merged SSD array was then bonded in parallel with a custom dipole receiving antenna, as shown in Fig. 2(a). A half-wave dipole antenna [see Fig. 2(b)] was connected to a network analyzer (Agilent Technologies – model E5061B ENA) via a coaxial cable to transmit a microwave signal with power P_{RF}. Both transmitting and receiving antennas have a similar resonance frequency at 890 MHz as observed from their S11-parameter plotted in Fig. 2(c). They were positioned at a distance d to each other. The detected dc output voltage, V_{out} was measured using a dc multimeter. Fig. 2(d) illustrates the measurement set up of this work. It is worth noticing that a balun was not utilized in the set up of the transmitting antenna since the S11-parameter of this antenna has exhibited the required and necessary narrow-band behavior.

3. Results and discussion

Fig. 3 shows the measurement results of V_{out} as a function of frequency, f, spanning from 0.1 to 1.5 GHz with different values of P_{RF} and d. As expected, each trace has a peak value at 890 MHz, the resonance frequency of the rectenna. The magnitude of the peak value increased as P_{RF} and d increased and reduced, respectively. Since both antennas were dipole, they were easily aligned to each other for maximum directional radiation and reception.

Fig. 4(a) shows the readings of V_{out} with respect to P_{RF}, measured at 890 MHz as the value of d was varied from 2 to 5 cm. Based on a small-signal approximation, the square-law detection behavior was observed in the region below −7 dBm. At much higher P_{RF}, in which the small-signal approximation is no longer

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