Sensitivity of Si-based zero-bias backward diodes for microwave detection

S.-Y. Park, R. Yu, S.-Y. Chung, P.R. Berger, P.E. Thompson and P. Fay

Silicon-based backward diodes incorporating δ-doped active regions for direct detection of microwave radiation with zero external DC bias have been demonstrated at room temperature and characterised for their sensitivity. The resulting backward diodes, which were grown by low temperature molecular beam epitaxy, show a high zero-bias curvature coefficient (γ) of 23.2 V^{-1} with a junction resistance (R_j) of 687 kΩ for a 5 µm diameter mesa diode. The microwave-frequency voltage sensitivity is reported for the first time; a measured sensitivity of 2376 V/W is obtained at zero-bias when driven from a 50 Ω source. An intrinsic 3 dB cutoff frequency of 1.8 GHz (5 µm diameter) was determined based on an extracted series resistance of 290 Ω and a junction capacitance of 0.307 pF using a small-signal model established to fit the measured *S*-parameters.

Introduction: Si-based backward diodes are a leading candidate for passive detection of millimetre-wave radiation. Their high zero-bias nonlinearity enables operation with no extra bias control circuits required, which dramatically reduces $1/f$ noise. Monolithic integration and registration with complementary metal-oxide-semiconductor (CMOS) or SiGe heterojunction bipolar transistor (HBT) readout circuitry is poised to leverage the silicon semiconductor industry for potential widespread usage of these sensor elements for security applications such as detection of concealed weapons.

Backward diodes, based on tunnelling and proposed by Esaki and Miyahara in the early 1960s [1], have been realised epitaxially, and are very good candidates for microwave detection compared to several alternative detector technologies in terms of their high sensitivity, low noise, simplicity and room temperature operation. A tunnelling backward detector enables the direct detection of microwave radiation without external applied bias, therefore no extra bias control circuits are required, resulting in a simplified system and reduced pixel complexity. This leads to a significant reduction of the total cost of fabrication and assembly [2]. Most backward-diode detectors utilise III-V compound-based heterojunctions, which are not readily compatible with mainstream silicon technology. Recently, the first high sensitivity Si-based backward diodes, grown by low-temperature molecular beam epitaxial (LT-MBE) growth, were demonstrated by Jin *et al.* [3], who reported a record Si-based curvature coefficient of 31 V^{-1} at zero bias, which is almost double that of a commercial discrete Ge backward diode at room temperature [4].

In this Letter, we report the first directly-measured microwave sensitivity performance of a zero-bias Si-based backward detector. A measured sensitivity of 2376 V/W was determined when driven from a 50 Ω source. A cutoff frequency of 1.8 GHz was extracted with a series resistance of 290 Ω and a junction capacitance of 0.307 pF for a 5 µm diameter mesa device. Here the structure was modified from the previous report [3] to reduce the junction resistance for better RF performance without a significant reduction in the zero-bias curvature coefficient.

Experiment: The schematic diagram of the Si-based backward diode structure used in this study is shown in Fig. 1*a*. Epitaxial growth was performed by low-temperature molecular beam epitaxy (LT-MBE) using elemental Si and Ge in electron-beam sources on Si (100) substrates (< 0.005 Ω cm). *p*- and *n*-type doping were achieved by evaporation from B and GaP in Knudsen cells, respectively. The backward diode structure utilised a Si buffer layer grown at 650°C on the Si substrate. The p^+-Si substrate contact layer (5×10^{19} cm^{-3}) was grown at 500°C. A 1 nm SiGe cladding layer is inserted below the contact layer to suppress B outdiffusion, followed by a B δ-doping layer (2.5×10^{13} cm^{-2}) deposited while the growth temperature was lowered from 500 to 320°C. Next, the active tunnelling region, a 4 nm undoped $Si_{0.6}Ge_{0.4}$ spacer layer and a 2 nm undoped Si layer, was grown at 320°C, followed by the deposition of a P δ-doping layer (2.5×10^{13} cm^{-2}). The top n^+ contact layer was grown at 400°C and consisted of a 100 nm n^+-Si layer (5×10^{19} cm^{-3}), a P δ-doping layer (1×10^{14} cm^{-2}), and a 5 nm undoped Si layer [5].

Prior to device fabrication, portions of the MBE wafer were annealed, separately, in a rapid thermal annealing (RTA) furnace at various temperatures for 60 s under a forming gas ambient (N_2/H_2). The anneal removes point defects, induced by the LT-MBE process, which significantly degrade the curvature coefficient [3]. Annealing temperatures between 850 and 890°C were investigated to determine the optimum annealing condition for a low junction resistance concurrently with a high curvature coefficient at zero bias.

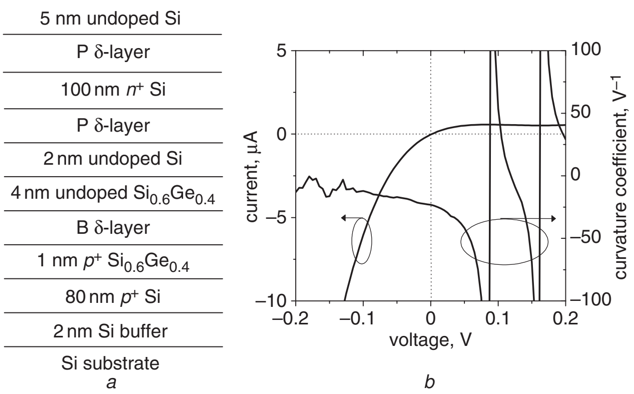

Fig. 1 *Schematic diagram of Si/SiGe backward diode structure grown by LT-MBE, and room temperature I-V characteristic and curvature coefficient (γ) against DC bias voltage for 5 µm diameter Si/SiGe backward diode*

a Schematic diagram
b Room temperature *I-V* characteristic and curvature coefficient (γ) against DC bias voltage

Device fabrication included circular cathode contact definition followed by deposition and lift-off of Ti/Cr/Au (150 Å/1500 Å/1000 Å) metal using electron beam evaporation. Self-aligned mesas were formed using wet etching in a $HF/H_2O/HNO_3$ (1:100:100) solution. The anode ohmic contact metal of Pt/Au (150 Å/1000 Å) was defined by lift-off photolithography and subsequent electron beam evaporation. A photo-definable polyimide process was then used to form a dielectric isolation layer to fashion via holes. Finally, the last lithography step defined the ground-signal-ground probe pads needed for RF measurement by deposition and lift-off of Ti/Au (150 Å/2000 Å).

Results: Fig.1*b* shows the room temperature *I-V* characteristic of a 5 µm diameter Si/SiGe backward diode illustrating a strong nonlinearity with a curvature coefficient ($\gamma = (d^2I/d^2V)/(dI/dV)$) of 23.2 V^{-1}, and an areal junction resistance of 13.5 MΩ μm^2 at zero bias. This compares favourably with the previous report [3] of a curvature coefficient of 31 V^{-1} and an areal junction resistance of 140 MΩ μm^2. In the previous report [3], 18 µm diameter Si/SiGe backward diodes grown at 320 and 400°C exhibited a junction resistance, R_j, of 22 and 550 kΩ, respectively. This is contrasted to a junction resistance of only 4 kΩ for the devices reported here of the same dimensions. The RF sensitivity (β_V) is directly proportional to the DC nonlinearity curvature coefficient through the approximation $\beta_V = 2Z_s\gamma$, where Z_s is the source impedance.

Si/SiGe backward diode detectors were characterised using on-wafer *S*-parameter measurements from 0.01 to 20 GHz in 0.34 GHz steps. De-embedding of the device from pad parasitics was based on *S*-parameter measurement of on-wafer short- and open-pad test structures. The measured data was fitted to a small-signal equivalent circuit model using Advanced Design System (ADS) software so as to obtain the intrinsic device parameters including series resistance (R_s), junction capacitance (C_j) and junction resistance (R_j). The intrinsic cutoff frequency, $f_c = 1/(2\pi R_s C_j)$, at zero bias for a 5 µm diameter mesa diode is estimated to be 1.8 GHz based on an extracted series resistance of 290 Ω and junction capacitance of 0.307 pF. This is limited in these first-generation devices by the ohmic contact resistances and by capacitive coupling to the conductive substrate.

Voltage sensitivity of these Si/SiGe backward diodes, defined as the DC voltage output developed across the detector divided by the available RF power incident on the detector, was measured on-wafer from 0.01 to 20 GHz against input power level. Fig. 2 shows the measured sensitivity and detector voltage characteristics of 5 µm mesa diameter diodes against input power at an RF frequency of 1 GHz. A 1 dB compression point of −10.26 dBm is observed. Table 1 shows the measured sensitivity against frequency from 0.01 to 20 GHz for a 5 µm diameter mesa detector driven by a 50 Ω source. The data in Table 1 indicate the device is well-modelled by a one-pole frequency response with an extrinsic 3 dB frequency of 1.2 GHz. This is consistent with the small-signal model obtained from measured *S*-parameters.

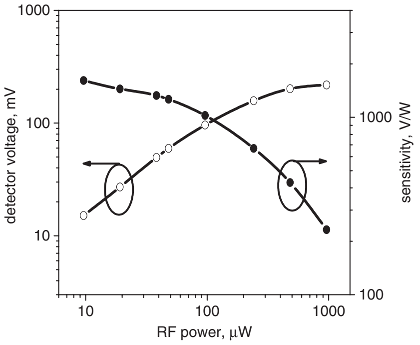

Fig. 2 *Measured sensitivity and detector voltage characteristics of 5 µm diameter mesa against input power at RF frequency of 1 GHz.*

Table 1: Sensitivity measurement against frequency from 0.01 to 20 GHz for 5 µm diameter mesa detector driven by 50 Ω source

Frequency (GHz)	Sensitivity (V/W)
0.01	2376
0.1	2344
0.2	2113
0.5	2022
1	1655
2	1386
5	628
10	269
20	182

Conclusion: Si-based backward diodes incorporating δ-doped active regions were grown by low temperature molecular beam epitaxy (LT-MBE) as zero bias detectors with high sensitivity and strong curvature coefficient. They were fabricated and the RF sensitivity measured for the first time. The maximum measured voltage sensitivity was 2376 V/W when driven with a 50 Ω source, which results in an intrinsic cutoff frequency of 1.8 GHz for a 5 µm diameter mesa diode. The measured *I-V* characteristics of the backward diodes show a high zero-bias curvature coefficient (γ) of 23.2 V^{-1} with an areal junction resistance of 13.5 MΩ µm^2. The junction resistance is one order of magnitude smaller than a previous report [3], leading to improved prospects for impedance matching in system applications.

Si-based backward diodes as zero bias detectors should be capable of cutoff frequency within the atmospheric window of 94 GHz for passive millimetre-wave detection with the usage of a low resistance Ni silicide ohmic technology [6], scaled size devices, and high-resistivity substrates.

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