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High frequency characteristic of a monolithic 500 °C OpAmp-RC integrator in SiC bipolar IC technology

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ABSTRACT

This paper presents a comprehensive investigation of the frequency response of a monolithic OpAmp-RC integrator implemented in a 4H-SiC bipolar IC technology. The circuits and devices have been measured and characterized from 27 to 500 °C. The devices have been modelled to identify that the substrate capacitance is a dominant factor affecting the OpAmp's high-frequency response. Large Miller compensation capacitors of more than 540 pF are required to ensure stability of the internal OpAmp. The measured unit-gain-bandwidth product of the OpAmp is ~1.1 MHz at 27 °C, and decreases to ~0.5 MHz at 500 °C mainly due to the reduction of the transistor's current gain. On the other hand, it is not necessary to compensate the integrator in a relatively wide bandwidth ~0.7 MHz over the investigated temperature range. At higher frequencies, the integrator's frequency response has been identified to be significantly affected by that of the OpAmp and load impedance. This work demonstrates the potential of this technology for high temperature applications requiring bandwidths of several megahertz.

1. Introduction

Silicon Carbide (SiC) is a wide-bandgap semiconductor that has demonstrated suitability for implementing extreme-temperature electronics, well beyond 300 °C [1]. SiC-based integrated circuits (ICs) can provide significant benefits for *in situ* sensor applications in harsh environments. For example, placing the pre-amplifier in close proximity to the capacitive sensors instead of using remote electronics can minimize signal attenuation and reduce noise and interference [2]. The operational amplifier (OpAmp), as well as its related integrator, is the main element in the mentioned system for realization of signal conditioning. A few high-temperature amplifiers implemented using different SiC technologies have been reported in [2–10]. N-type MOSFET SiC amplifiers have been demonstrated to operate up to 350 [3] and 300 °C [4], and lately [5] has been pushed to 500 °C, although struggling with gate-oxide reliability at high temperatures. On the other hand, JFET SiC amplifiers have demonstrated stable operation for thousands of hours at ambient temperature up to 576 °C [6,7]. Similar to JFETs, bipolar junction transistors (BJTs) operate solely using highly stable SiC pn junctions, which potentially allows durable high temperature operation. Moreover, compared to FETs, BJTs are potentially better for high-speed analog ICs [8]. Recently, BJT amplifiers have been reported to operate up to 500 °C using 4H-SiC BJT technology [9,10], which mainly demonstrated the circuits' low-frequency performances. However, the high frequency response of the OpAmp and its related integrator is of importance in many applications including active RC filters and RC oscillators.

This paper investigates the high frequency characteristics of a monolithic SiC BJT integrator and its internal OpAmp, whose schematic and fabricated chip-photo are shown in Figs. 1 and 2 respectively. All components are implemented on-chip except the compensation capacitors C_C, which require large area in this technology (~30 pF/mm^2). Note that, the common-mode feedback (CMFB) and input base-current compensation circuits are not the main concern in this work, which have been described in detail in [10]. In Section 2, the results from the characterization and modeling of selected devices including BJT, integrated resistor and capacitor are presented from 27 to 500 °C, and used for analyzing the circuits' performance presented in Section 3. A conclusion is provided in Section 4 including areas of future attention that will enhance the further application of this technology.

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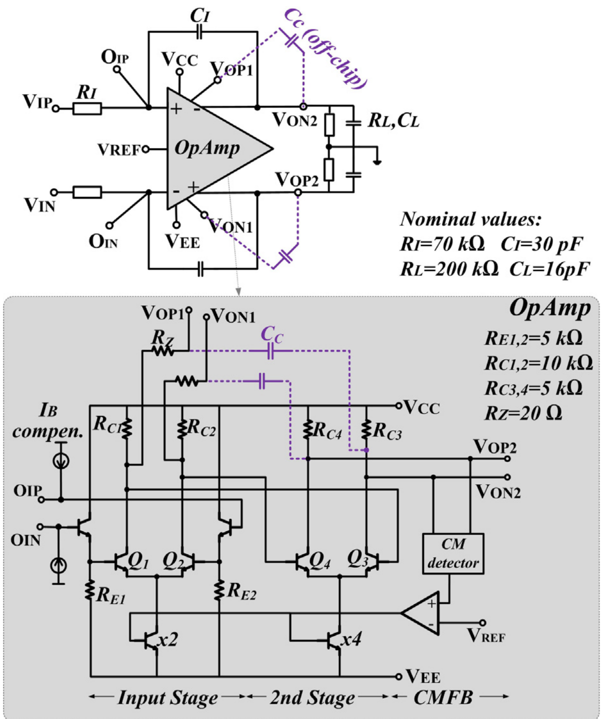

Fig. 1. Schematic of the integrator and its internal Op-Amp (all components are implemented on-chip except the compensation capacitors C_C).

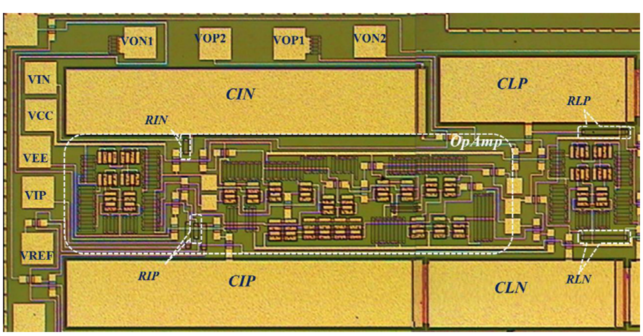

Fig. 2. Micro-photograph of the fabricated chip (integrator, internal OpAmp, integrating and load resistors, capacitors and pins are denoted according to Fig. 1).

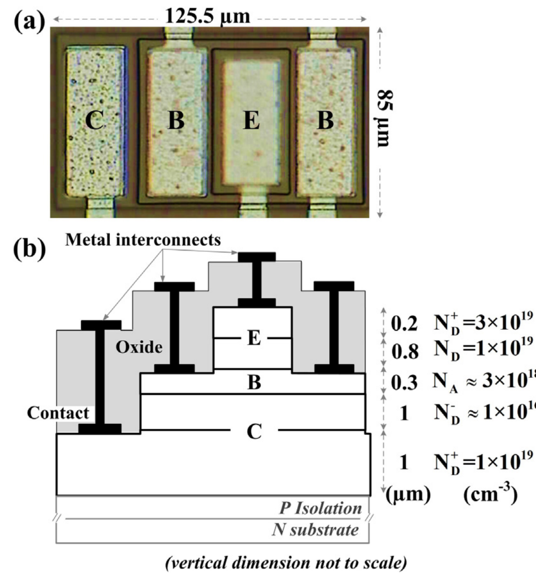

Fig. 3. SiC NPN BJT's (a) top-view optical image and (b) cross-section view with doping concentration and thickness indicated for the corresponding epi-layer.

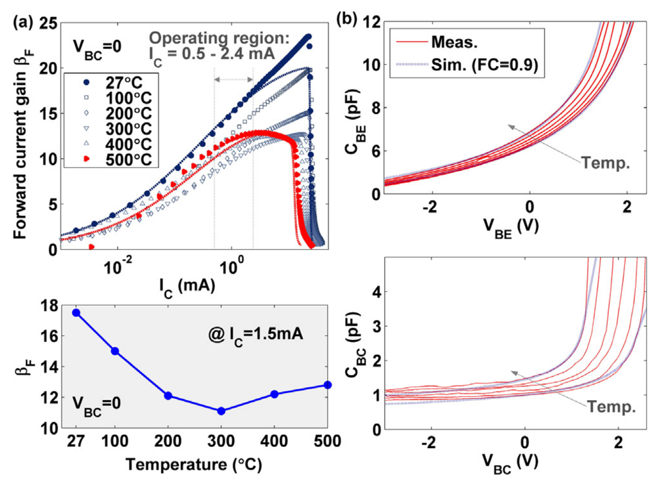

Fig. 4. Selected SiC BJT's DC and AC performances from 27 to 500 °C: (a) Measured β_F vs. I_C (symbols) and simulated results at 27 and 500 °C (dashed-line); the temperature dependence of the β_F at $I_C = 1.5$ mA. (b) Meausred C-V characteristics of B-E and B-C junction (solid-line) and simulation results at 27 and 500 °C (dotted-line).

2. Device characterization and modelling

2.1. NPN BJT

The BJT, as well as the passives, were fabricated using our in-house bipolar IC technology on 4-inch 4H-SiC wafers. The developed process involved dry etching of doped SiC epi-layers in three stages to isolate the emitter(E), base(B) and collector(E) region. Separate ohmic contacts were used for n-type and p-type regions. One metal layer was used for interconnects. The process details are described in [11]. The NPN BJT's top-view optical image and the cross-section view are illustrated in Fig. 3(a) and (b) respectively, in which the doping concentration and thickness for the corresponding epi-layer are indicated. To reduce variation between devices, all BJTs had the same size in the circuit, and differential pairs were oriented the same way in the layout for symmetry.

The forward current gain β_F is the most important parameter for the circuit performance, which was measured versus collector current from 27 to 500 °C as shown in Fig. 4(a) (*The selected BJT is on the same die near the tested circuit*). Accordingly, Spice Gummel-Poon (SGP) models were extracted at six temperature values over the considered temperature range, and two simulation results at 27 and 500 °C are plotted in Fig. 4(a) for comparison. Although the models are not highly accurate, they are sufficient for simulating the circuits intended to be biased at 0.5–2.4 mA. To be noted, in the circuit's operating region, the temperature dependence of average β_F is not monotonic. This behavior can be attributed to two competing mechanisms that affect β_F when the temperature increases: reduction of the emitter injection efficiency due to increased ionization of base dopants and increase of carrier lifetime [12].

The junction capacitances of base-emitter (C_{BE}) and base-collector (C_{BC}) versus applied voltages were also measured and modelled in the investigated temperature range as shown in Fig. 4(b). The temperature dependences of the zero-biased junction capacitances *CJE* and *CJC* are 6.2 and 1 pF respectively at 27 °C, and