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Punch through float-zone silicon phototransistors with high linearity and sensitivity

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Abstract

In this paper, we propose, analyze and demonstrate a high-purity float-zone (FZ) silicon phototransistor operating at the punch through state with high linearity and sensitivity. Those phototransistors were fabricated on high-purity FZ silicon substrates; the dependence of the sensitivity on incident optical power and bias voltages has been investigated to light with a wavelength of 0.83 μm from a laser diode. In accordance with theoretical prediction, it shows that the linearity reaches the highest when the base of the phototransistor is completely depleted (punch through), and the fitting goodness of output R^2 is 0.9954 over a 40 dB range from 0.15 to 1500 nW. The sensitivity of the phototransistor can be as large as 40–70 A/W at the punch through state, which is equivalent to an internal current conversion gain of about 75–130. The stability of 1% in the sensitivity for the punch through phototransistor with an internal current conversion gain of 130 can be obtained if the bias voltage and operating temperature can be stable to about 2.5% (1 in 40 V) and the temperature to $\pm 2\,^{\circ}$C.

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Keywords: Linearity; Punch through; Phototransistor; Silicon detector; Float-zone silicon

1. Introduction

A bipolar phototransistor is attractive as a particle detector [1–5] or as an image sensor in a fingerprint system [6]. When it is used as a particle detector, the linearity may be essential since it determines the energy resolution; in the analog imaging process, the photocurrent should be approximately linear with the incident optical power in order to avoid distortion of the captured image. Since the float-zone (FZ) silicon has lower contamination and longer minority carrier lifetime

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than those in Czochralski silicon and other semiconductor materials, one of the authors reported that it has potential advantages to fabricate phototransistors on FZ silicon to achieve a high sensitivity at ultra-low-signal levels [7,8]. High gain up to 4400 for 0.17 nW light with a wavelength of 0.83 μm [7] has been demonstrated. However, the linearity of these phototransistors (i.e., sensitivity changes with incident optical power) was poor compare to avalanche photodiode (APD) or photodiode, thus has limited their practical applications. Wang et al. [9] reported a GaAs–AlGaAs heterojunction phototransistor with a punch-through base as a low noise and high-speed detector, its fitting goodness of output R^2 was demonstrated to be 0.9999 over a 20 dB range of incident optical power from 0.2 to 20 μW. Later, a modified punch through phototransistor with avalanche enhancement and a guard ring structure was reported by one of the authors, strong dependence of sensitivity and linearity on incident optical powers and collector voltages was observed [10]. More recently, a phototransistor with conventional structure that was used as current-mode CMOS image sensor was reported to have the fitting goodness of output voltages R^2 value of 0.97 in the linear region [11].

Considerable efforts have been expended in the design of various structures of bipolar photodetectors [9–16]. Among those device structures, the bulk-barrier [17] photodiodes, including triangular-barrier diodes and camel diodes, have been attracted much attentions. In contrast to triangular-barrier diodes [9–12,16] which have symmetric p^+–n–p^+ or n^+–p–n^+ structures, camel diodes [13–16] have an asymmetric doping profile that is similar to the punch through phototransistor discussed in this paper. FZ silicon phototransistors have potential advantages over camel diodes in compatibility with bipolar integrated circuits, low dark current, and flexibility in operations.

There are few reports on the issue of the linearity of the phototransistors (i.e., the relationship between the photocurrents and the optical powers) [9–10]. Analytical expressions derived for the optical gain of a conventional HPT [18] can be utilized to optimize the design for the current gain of the conventional phototransistors. However, they did not explicitly offer the dependence of the optical gain on incident optical power. Although theoretical discussions were addressed to photocurrent amplification mechanism in majority-carrier bulk-barrier photodiodes in the post punch through state [13–15,19], those photodiodes are nonlinear optical devices, the carrier transportation mechanism in the completely depleted bulk was not discussed in detail under or at the apunch through state.

In this paper, we propose, analyze and demonstrate a high-purity FZ silicon phototransistor operating at the punch through state with high linearity and sensitivity. The theoretical analysis on its linearity, involved with minority carrier transport mechanism is presented first, followed by the fabrication process of the devices, then the experimental results and discussion on its characteristics of linearity, sensitivity, spectral response, optoelectronic switching and the tolerance on bias voltage and operating temperature are presented, and a conclusion is given in the end.

2. Theoretical analysis and numerical calculations

Fig. 1 shows schematically the structure and the corresponding energy band diagram of an n^+–p–n phototransistor. It is biased with a voltage V_{ce} between the emitter and the collector, leaving the base floating. The doping concentration of Emitter, Base and Collector is N_E, N_B and N_C, respectively. The thickness of the base is d and the width of neutral base is W. With the increase of V_{ce}, the depletion layer of the reverse-biased base–collector (BC) junction may pass through the base region, and reach the depletion layer of the slightly forward-biased emitter–base (BE) junction. In this situation, the base of the phototransistor is completely depleted and the device reaches punch through. In this study, we will focus the discussion on the linearity and the sensitivity of this type of phototransistor under DC operating conditions.

The current of a conventional phototransistor without light illumination (i.e., dark current) is