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Review

Silicon diode temperature sensors—A review of applications

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ABSTRACT

Most of the variables measured in scientific investigations or engineering applications depend, by varying degrees, on temperature. This necessitates the simultaneous measurement of temperature along with the variable of interest in order to perform high fidelity temperature compensated measurements. Silicon diode based temperature sensors (or silicon thermodiodes) have the advantages of being low cost, having an absolute temperature measurement capability as well as providing the option of on-chip integration with electronic circuits and a wide temperature measurement range. Leveraging these advantages, engineers and scientists have used silicon thermodiodes in numerous and diverse applications. This paper identifies the common temperature measuring techniques, and focuses on the use and advantages offered by silicon diodes operated as temperature sensors in different drive modes. Finally it explores the published literature for summarizing the application areas where such sensors have been utilized successfully in recent years.

Contents

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1. Introduction

Temperature is one of the most important and commonly measured physical quantities. Consequently, temperature sensors cover the largest segment of the sensor market by volume [1]. Many of the physical phenomena being sensed and measured (e.g., humidity, pressure, flow, stress and gas concentration) have some temperature dependence and therefore, need to be compensated for temperature variations. Major applications of temperature sensors are thus focused at sensing temperature for thermal compensation.

With ongoing advancements in CMOS (complementary metal oxide semiconductor) and micro-fabrication technology in recent years, requirements for smaller size, lower power consumption, wider temperature ranges and on chip sensor-electronics integration have challenged the conventional temperature measurement techniques. To fulfill these stringent requirements, silicon diodes and transistors are increasingly being used as temperature sensors.

The silicon p–n junction diodes are the most accurate CMOS temperature sensors and many researchers in a wide variety of applications have used them for sensing temperature, mainly due to their accuracy, compatibility with IC (integrated circuit) technology and low manufacturing costs [2].

When the base and collector of a silicon BJT (bipolar junction transistors) are shorted, it can be operated as a diode and used as a temperature sensor. A number of researchers have instead used diode connected BJTs for temperature sensing because in a diode-connected BJT, the effect of material, geometric and process variations associated with diode manufacturing process are removed. Moreover, some CMOS design kits only offer the option of a diode-connected BJT and not a standalone diode. Significant research on diode-connected BJTs has been reported by a research group at Delft University [3–5]. Similarly, diode-connected metal–oxide–semiconductor field-effect transistors (MOSFET) are also used for temperature sensing though their nonlinear response has been a limiting factor [2]. However, on-chip temperature measurements with improved linearity [6,7], layout area, current consumption and sensitivity to thermal variations [7,8] of diode-connected MOSFETs, as compared to the ones based on BJTs, have recently been reported.

Section 2 of the paper identifies various temperature sensing techniques. Utilization and advantages of silicon diodes operated as temperature sensors are discussed in Section 3. In Section 4, various biasing techniques that are best suited for silicon thermodiodes in particular situations are elaborated. Finally, a detailed review of silicon diode temperature sensors focusing on application areas where they have been successfully utilized by researchers are highlighted.

2. Temperature sensing techniques

There are a variety of techniques employed for sensing temperature which utilize diverse physical phenomenon like thermal expansion [9], thermoelectricity [10], fluorescence [11], etc. Selection of any of these techniques depends upon specific requirements or constraints. For example, a sensor may be required to establish direct contact with the environment of which the temperature is being measured, or on the contrary, it may not be desirable at all for the sensor to have any contact with the environment.

From the point of view of the relative position of the sensor and the environment, temperature measuring systems may be divided into three main categories: invasive, semi-invasive and non-invasive [9,12,13]. Each of these categories has distinct characteristics and limitations. Invasive temperature measurement systems have a direct contact with the environment of which the temperature is being measured. Examples of such systems include the common liquid-in-glass thermometers, gas thermometers, thermoelectric devices like thermocouples, electrical resistance devices like platinum resistance temperature detectors and thermistors, and semiconductor devices. Semi-invasive temperature measurement systems enable remote observation like change of colour for temperature detection. Thermonic liquid crystals, thermographic phosphorus and heat sensitive paints are a few examples of semi-invasive techniques. The non-invasive temperature measurement systems have no contact with the environment of interest. Examples of such systems include infrared thermography, absorption and emission spectroscopy and acoustic thermography. Detailed elaborations on theoretical background, advantages and limitations of each category may be found elsewhere [9,12].

Out of all the techniques available for sensing temperature, selection of the best suited technique depends on various factors like the required accuracy, range, response time, size, cost, fabrication limitations, robustness, electrical circuit simplicity, integration requirements etc. An excellent overview of the techniques generally employed for sensing temperatures along with a comprehensive guide highlighting different merits and demerits of each technique is given by Childs et al. [9]. Similarly, Altet et al. [12] and Blackburn [13] have consolidated various measurement techniques for temperature sensing in ICs. A comparison between resistance temperature detectors (RTDs) and diodes for chip temperature measurements, in the context of techniques used for reducing uncertainty and errors during measurements, is presented by [14]. More recently, Udrea et al. [2] have reviewed state of the art in IC temperature measurements with special focus on CMOS technology.

3. Use and advantages of silicon diode temperature sensors

Diodes can be used for temperature sensing due to the strong temperature dependence of their forward bias voltage drop. Many different semiconductor materials have been reported in literature for diode temperature sensors (silicon, germanium and selenium are some examples). Exploiting this behaviour of silicon diodes, their earliest use as temperature sensors was reported by Harris [15] and McNamara [16]. In recent years, interest in using silicon diodes as temperature sensors was further fuelled by a number of merits associated with them. Most importantly, they (a) have a very low cost [2,9], (b) exhibit a simple voltage temperature relationship over a wide range (4.2 to 888 K) [17–21], (c) can be integrated with the electronics on the same chip [2,9], (d) measure absolute temperature, and (e) exhibit reasonable sensitivity (around 2.5 mV/K) and accuracy (of the order of $\pm$50 m K after calibration) [9]. In addition, the performance deterioration associated with self-heating can be taken care of by operating silicon thermodiodes at very low currents [2,9]. Careful calibration is, however, required for measurements in cryogenic range, and noise reduction techniques should be adopted to avoid ac component in constant current supply. More recently, a number of CMOS and discrete MEMS (Micro Electro Mechanical Systems) sensors [22–28] have used the thin silicon layer of a commercially available silicon on insulator (SOI)