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High-precision and low-cost wireless 16-channel measurement system for multi-layer thin film characterization

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ABSTRACT

A novel automatic multi-channel measurement system is developed for evaluation of multi-layer thin films. With the aim to solve the unsuitability of conventional four-probe measurements with van der Pauw and Montgomery configurations for multi-layer thin film structure, this measurement system can acquire the temperature coefficient of resistance (TCR) and the *I–V* characteristics of multi-layer thin films. The wireless technology adopted in this measurement system separates the data acquisition and control circuit, which facilitates the application of the system. The maximum measurement capability of multi-channel acquisition system is 16 samples in a batch. The present work also proposes a highly accurate resistance measurement method for characterizing the multi-layer thin films. The advantages of this system include perfect functions, user-friendly interface, high integration and low-cost. The practical application of the system demonstrates a measurement error less than 0.005% of sample resistance. The testing results show that this system performed well in multi-layer thin film measurement.

1. Introduction

Bolometers widely manufactured for anti-collision sensors and night vision equipment for the automobile industry. Uncooled bolometers have become the preferred choice for IR detection in both military and civil applications during last decade [1]. These detectors operate at room temperature through the response of a thermistor material to temperature variations. Vanadium oxide (VOx) [2], amorphous and poly-crystalline Si, as well as SiGe are typical thermistor materials for IR detection. Significant characteristics of a thermistor material include a high-temperature coefficient of resistance (TCR) and high signal-to-noise ratio. Multiple quantum well (MQW) film has recently been recognized as a new low-cost thermistor material for infrared (IR) detection and biological applications [3,4]. $Si_{1-x}Ge_x/Si$ MQW structure has recently been proposed as a new thermistor material [5]. The thermistor's single-crystalline material exhibits very low $1/f$ noise, which makes this material have more advantages as a biosensor than traditional ones [6–8]. Combining with the microsystem technology, the sensor can be typically made in a small volume which enables a low thermal capacity and a short response time [9,10].

Functioning as the thermistor material, the quantum well film changes its resistance as the temperature varies, which can be quantified by TCR, defined as:

$$\alpha = \frac{1}{R} \times \frac{\partial R}{\partial T} \tag{1}$$

where R is the resistance, and T is the temperature. For a semiconducting material, $1/R$ is proportional to the amount of free carriers. To achieve high sensitivity, the TCR should be as high as possible, whereas the noise resulting from contacts and the material should be low. TCR and $I–V$ characteristics of the material are critical for the appropriate application of the material such as bolometer and readout circuit design.

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Nomenclature

HD	voltage detection end (−)
HS	voltage detection end (+)
I_S	current flowing through R_S (A)
I_X	bias current flowing through R_X (A)
K_1	total gain of channel 1
K_2	total gain of channel 2
K_3	total gain of channel 3
K_4	total gain of channel 4
LD	current excitation end (−)
LS	current excitation end (+)
R	resistance (Ω)
R_0	current limiting resistor (Ω)
R_S	high-precision standard resistance (Ω)
R_X	sample resistance (Ω)
S_0	switch control low bit
S_1	switch control high bit
S_{I-V}	measurement mode switch
T	temperature (K)
T–R	temperature–resistance
V_{D1}	HS voltage (V)
V_{D2}	HD voltage (V)
V_{D3}	LS voltage (V)
V_{D4}	LD voltage (V)
V_{r1}	AD reference voltage of channel 1 (V)
V_{r2}	AD reference voltage of channel 2 (V)
V_{r3}	AD reference voltage of channel 3 (V)
V_{r4}	AD reference voltage of channel 4 (V)
V_{ref}	reference voltage (2.5 V)
V_{S+}	S+ end voltage (V)
V_{S-}	S− end voltage (V)
V_{X+}	X+ end voltage (V)
V_{X-}	X− end voltage (V)
ΔV_1	total offset of channel 1 (V)
ΔV_2	total offset of channel 2 (V)
ΔV_3	total offset of channel 3 (V)
ΔV_4	total offset of channel 4 (V)

Greek symbols

α	temperature coefficient

Subscripts

I–V	current–voltage
ref	reference voltage
S+	high-level voltage port of standard resistance
S−	low-level voltage port of standard resistance
X+	high-level voltage port of film samples
X−	low-level voltage port of film samples

For metallic and superconducting samples, the magnitude of the resistance to be measured is small. The conventional four-probe technique is used to eliminate the contact resistance between the sample and electrical contacts. These measurements are performed by passing a constant current to one pair of electrical leads and measuring the potential attributed to the resistance of the specimen using another pair of leads [11]. However, conventional four-probe measurements with van der Pauw and Montgomery configurations are unsuitable for MQW film because the direction of electron mobility in MQW structure is not along the surface but along the longitudinal direction of the material [12–14]. As a result, constructing a suitable electrical test system for this multi-layer structure is necessary [15–17].

To conque this challenge, a number of electrical test systems for MQW structure has been reported. Reedholm[TR] has developed a high-precision test system [18], which requires at least three VFIF's and one DMM-16. Besides, professional training is required for the users before using these instruments to conduct the MQW film test. Another high-precision test system given in [19–21] requires an additional external voltmeter to record the experimental data, and the calibration of the MQW film cannot be completed automatically. A probe measurement system proposed in [22,23] does not require a package for the etched structures to be tested. However, this probe measurement system is expensive. Some other TCR test systems are also presented but not for the multi-layer thin film [24–26].

In this work, we developed a measurement system with features of high-precision, low-cost and user-friendly for MQW film evaluation, which does not require additional voltmeters and professional training for the users. The system can test both the TCR and the I–V characteristics with the simultaneous measurements 16 samples. The wireless communication module of the system separates the measurement circuit from the control circuit, which facilitates the application of the system. A high-precision resistance test method is also proposed to improve the measurement precision of the MQW film. Besides, the working principle and the detailed design of the measurement system, including the hardware, the software and system characteristics, are expounded.

2. Method and architecture of the measurement system

2.1. Hardware system

A novel automatic measurement system was designed to measure the MWQ film, including the TCR and the I–V characteristics, as shown in Fig. 1. The system comprises a temperature chamber, detector and control chamber, as well as a control and data processing terminal. The measurement system structure schematic is shown in Fig. 2.

The temperature chamber with 0.1 K temperature control accuracy is used to control temperature in a range from 200 K to 380 K. Semiconductor TEC is used to control the temperature in the temperature chamber. A sample chamber inside the temperature chamber comprises radiation shields made of copper, and a copper sample holder is