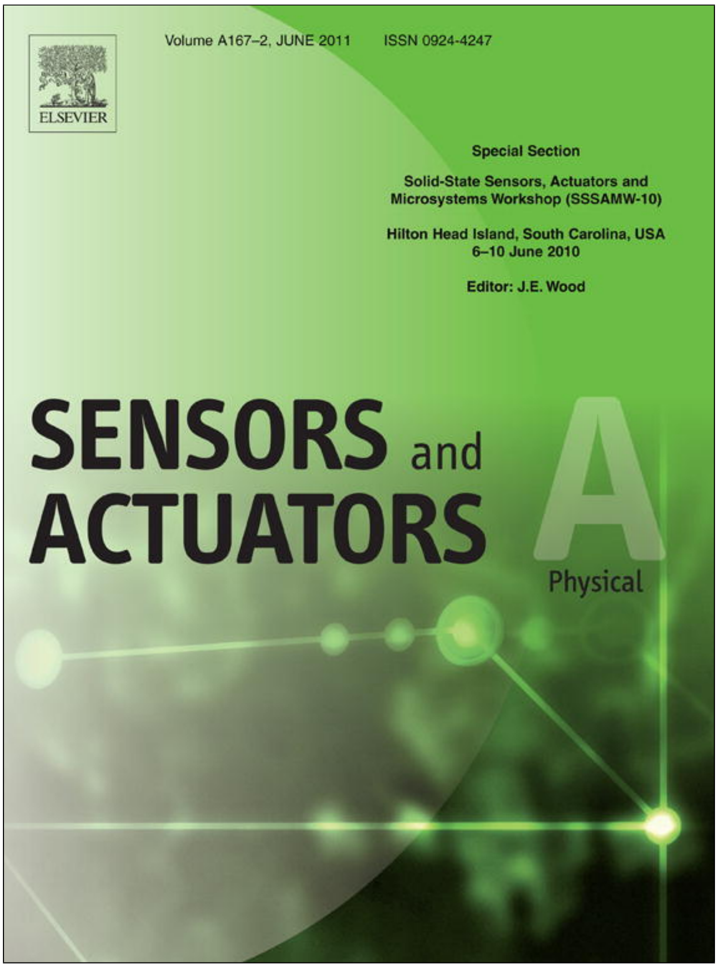
Volume A167–2, JUNE 2011 ISSN 0924-4247
ELSEVIER
Special Section
Solid-State Sensors, Actuators and Microsystems Workshop (SSSAMW-10)
Hilton Head Island, South Carolina, USA
6–10 June 2010
Editor: J.E. Wood
SENSORS and ACTUATORS
A
Physical

Sensors and Actuators A 167 (2011) 245–248

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Highly sensitive GaAs/AlGaAs heterojunction bolometer

P.K.D.D.P. Pitigala [a], P.V.V. Jayaweera [a], S.G. Matsik [a], A.G.U. Perera [a,*], H.C. Liu [b]

[a] *Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303, USA*
[b] *Institute for Microstructural Sciences, National Research Council, Ottawa K1A 0R6, Canada*

ARTICLE INFO

Article history:
Received 3 September 2010
Received in revised form 1 February 2011
Accepted 2 February 2011
Available online 25 February 2011

PACS:
07.57Kp
95.55 Rg
85.25Pb
85.60Gz

Keywords:
GaAs/AlGaAs
TCR
Bolometer
Room temperature

ABSTRACT

GaAs/AlGaAs multilayer heterojunction structures with different aluminum (Al) fractions and emitter doping densities were tested to identify optimum parameters for high temperature coefficient of resistance (TCR). Higher Al fractions and lower doping densities showed higher TCR. Additionally, p-doped heterojunction structures showed a higher TCR compared to an n-doped one with similar parameters. A p-doped multilayer superlattice heterojunction structure with 30 periods of GaAs/$Al_{0.57}Ga_{0.43}As$ junctions, operating at room temperature showed a TCR of ~4% and bolometer like infrared (IR) response up to 20 μm with a D^* of 1.7×10^6 Jones. This TCR is higher than that of VO_x or α-Si bolometers. At low temperatures (50 K) some of these devices have shown TCR values of over 30%.

1. Introduction

A wide variety of thermal and photon techniques have been tested to detect IR radiation. Among them thermal detectors utilize the temperature-dependent properties of the detector material [1]. As an example, devices such as thermocouples and thermopiles use the thermoelectric effect; bolometers and microbolometers [2] respond to changes in resistance; Golay cells [3] use the thermal expansion; and pyroelectric detectors [4] utilize the temperature dependent spontaneous electric polarization that generates electric charges upon incidence IR irradiation (known as pyroelectric effect). Bolometers utilize changes in the absorber temperature when irradiated with electromagnetic radiation. Change in temperature is usually measured as a resistance change in the semiconducting material. The change in the relative resistance per one degree of Kelvin (K) is defined as the temperature coefficient of resistance (TCR, β), and is the key parameter in determining the performance of the material.

The TCR (β) is defined as follows, where R denotes the resistance and T denotes the temperature. Additionally, R is proportional to the carrier concentration (N) hence, TCR is also proportional to carrier concentration.

$$\beta = \frac{1}{R}\left(\frac{\partial R}{\partial T}\right) \approx -\frac{1}{N}\left(\frac{\partial N}{\partial T}\right)$$

The maximum change in resistance for each degree of temperature difference and low noise characteristics are desirable to obtain the highest sensitivity in a thermal detector. Materials such as vanadium oxide (VO_x) or amorphous silicon (α-Si) were utilized in presently established bolometers. The main drawbacks of thermal detectors (bolometers) compared to other photon detectors are slow response time and high noise (such as $1/f$ noise, Johnson noise, thermal and background fluctuation noise [5]) and low TCR values. With the advancement in micro-machining techniques, miniature micro-bolometer structures have been developed and often used in uncooled thermal cameras. Although VO_x has a good bolometer performance with TCR ~2% K^{-1}, this exotic material is not well suited for large-scale CMOS production, due to the high temperature process used in fabricating VO_x for post-CMOS processes. On the other hand, amorphous silicon (α-Si) exhibits better TCR (~2.8% K^{-1}) compared to VO_x and, germanium silicon alloy micro-bolometers have the best TCR around 5% K^{-1}. This paper presents a GaAs/AlGaAs heterostructure with TCR values higher compared to existing VO_x or α-Si bolometers and close to micro-bolometers of Ge/Si alloy. A properly optimized GaAs/AlGaAs heterostructure would be a competitive candidate, as a micro-bolometer with high

* Corresponding author. Tel.: +1 404 413 6037; fax: +1 404 413 6025.
E-mail address: uperera@gsu.edu (A.G.U. Perera).

0924-4247/$ – see front matter
doi:10.1016/j.sna.2011.02.017

Table 1
List of detector structures used in TCR calculations and brief description of their parameters.

Sample	Al %	Doping density (p/n)	No. of layers in super lattice	TCR % (temperature (K))
HE0204	12	1×10^{18} (p)	12	30.6 ± 0.2 (50 K)
HE0205	12	3×10^{17} (p)	12	31.5 ± 0.2 (50 K)
HE0206	12	1×10^{17} (p)	12	33.4 ± 0.3 (50 K)
1329	12	4×10^{17} (n)	12	18.7 ± 0.2 (50 K)
SP001	28	3×10^{18} (p)	30	5.5 ± 0.4 (140 K)
SP002	37	3×10^{18} (p)	30	6.6 ± 0.3 (140 K)
SP003	57	3×10^{18} (p)	30	8.1 ± 0.4 (140 K)
				4.0 ± 0.5 (300 K)

detectivity due to the high TCR, especially compared to existing bolometers fabricated using VO_x or Si. Results presented in this paper show a competitive TCR value of 4% K^{-1} with detectivity (D^*) 1.7×10^6 Jones for a 400 μm × 400 μm pixel.

2. Experimental

Samples considered in this study are multilayer heterojunction (HEJ) structures based on doped GaAs emitters and undoped AlGaAs barriers. The dependency of the TCR on several different detector parameters such as doping density and Al fraction is investigated. A summary of parameters of these device structures is shown in Table 1. These detector structures were measured for their current–voltage–temperature (*IVT*) characteristics with the variation of temperature and voltage in small steps.

Although there are thin layers of emitter/barrier regions sandwiched in these HEJ superlattice structures they will not form any discrete quantum states inside the barrier/emitter/barrier layers due to their thickness. These emitters are doped high enough to have a scattering length similar to the emitter thickness. The result is a bound 3D carrier distribution in the emitter region. The structures were grown on semi-insulating GaAs substrates and were processed by wet etching to form square pixels with 400 μm × 400 μm in area. Ti/Pt/Au was evaporated on to the top and bottom contact layers. All the sample structures listed in Table 1 are prepared by the same procedure. A sample pixel from the structure SP003 that was suspended in midair at the center of a regular sample holder using gold wire was measured for the bolometric response. Two of such samples were measured, and both of them have shown a similar response.

The *IVT* characteristics of each structure were measured using a KEITHLEY 2400 source meter, after mounting them on a cold finger of a closed cycle refrigerator. The temperature was controlled by a Lake Shore 300 temperature controller system. The noise current density of the device was measured using a Stanford Research SR785 Fourier Transform dynamic signal analyzer coupled with a low noise current amplifier, Stanford Research SR570. The IR response of the device was measured using a Perkin-Elmer 2000 FTIR system.

3. Results and discussion

Initially, three structures (HE0206, HE0205 and HE0204) were used to study the dependence of TCR on the doping density. These three HEJ samples have identical structures except for the emitter doping densities, which are 1×10^{17}, 3×10^{17}, and 10×10^{17} cm^{-3} respectively. The results show a decreasing trend in the TCR with increasing doping density. The TCR of these three detectors (summarized in Table 1) were calculated at 50 K. At higher temperatures the resistance of these devices becomes very small; hence, the safe current limit is reached upon applying few millivolts. Therefore, an accurate calculation of TCR is difficult at higher temperatures for those three detectors. The dependency of TCR with the emitter

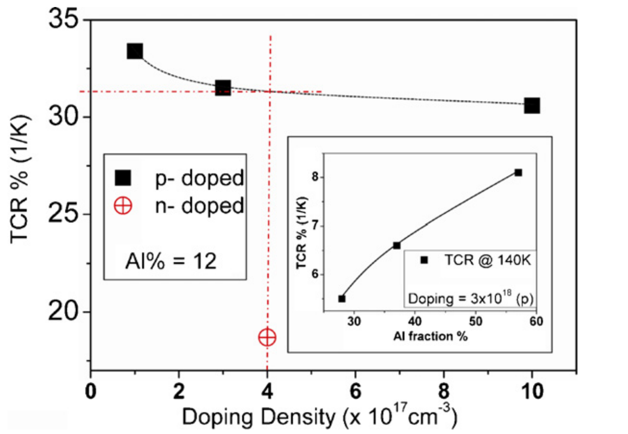

Fig. 1. Variation of TCR with doping density of a multilayer heterojunction structure. The structure consists with 12 layers of GaAs/AlGaAs emitter barrier regions (squire p-doped and circle n-doped). TCR values are calculated at the temperature 50 K with 1 V bias across the structure. The dotted lines (horizontal and vertical) show the intercept point of the TCR interpolated curve for a 4×10^{17} cm^{-3} p-doped structure. *Inset*: Variation of TCR with Al fraction of a multilayer heterojunction structure. The structure consists of 30 layers of GaAs/AlGaAs emitter/barrier regions with 3×10^{18} cm^{-3} p-doped emitter regions. TCR values are calculated at the temperature 140 K with 1 V bias across the structure.

doping density, at 1 V bias voltage across the top and the bottom contact, is illustrated in Fig. 1. A maximum TCR of 33.4 ± 0.3% K^{-1} was observed for 1×10^{17} cm^{-3} doped sample (HE0206) at 50 K. Work by Wissmar et al. [6] shows a similar behavior with the doping density for quantum well structures.

A further study using an n-doped structure (Sample # 1329) with similar parameters as above structures except for the emitter doping density of 4×10^{17} cm^{-3}, gave a TCR value of 18.7 ± 0.2% K^{-1} at 50 K, with 1 V bias applied across the detector (shown by the filled circle in Fig. 1). The p-doped structure having a doping density closest to 1329 is the HE0205 (3×10^{17} cm^{-3} (p)), and it shows a TCR around 31.5 ± 0.2% K^{-1} at 50 K. A TCR value of ~31% K^{-1} was estimated for a 4×10^{17} cm^{-3} p-doped device by interpolating the data in Fig. 1 (TCR vs doping). This observation predicts that the TCR of p-doped structures is higher compared to n-doped structures. A study by Sun et al. [7] shows a low carrier density (N) and a steeper gradient in carrier density with temperature (dN/dT) for p-doped structures compared to the n-doped structure from temperatures around 300 K down to 80 K. This implies a higher variation in the resistance in p-doped structures compared to n-doped structures with variation of temperature. As a result, a better TCR is possible in p-doped structures compared to n-doped structures.

The inset to Fig. 1 shows a TCR variation with the Al fraction, in the barrier layer, of p-doped GaAs/AlGaAs structures SP001, SP002 and SP003. All three sample structures contain 30 periods of undoped AlGaAs barriers and 3×10^{18} cm^{-3} p-doped GaAs emitters. The Al fraction (x) in $Al_xGa_{1-x}As$ barrier layers are 28%, 37% and 57% respectively in these three devices respectively. For com-

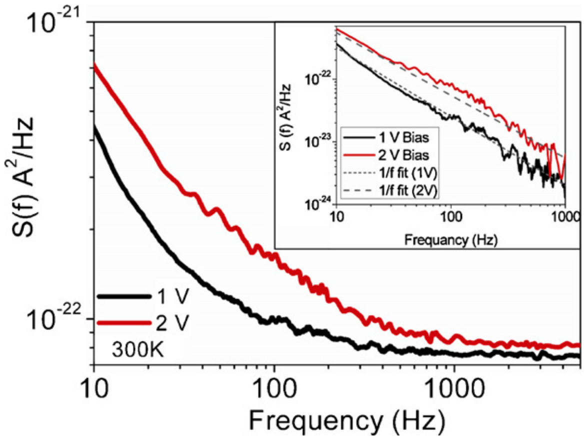

Fig. 2. Noise current density ($S(f)$) and fitted data (for 1 V and 2 V bias) of the sample illustrated in the inset. *Inset*: The noise spectra after baseline correction. Dotted lines indicate the $1/f$ fitted curves for 1 V and 2 V biases.

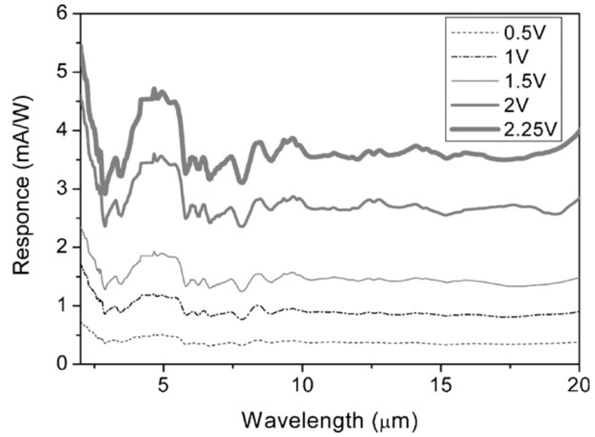

Fig. 3. Responsivity of the sample consisting of 30 layers of GaAs/AlGaAs junctions with 3×10^{18} cm^{-3} p-doped GaAs regions and Al fraction of 57% (SP003), at different bias voltages.

parison of TCR values of these three samples, the measurements were carried at 140 K (maximum operating temperature of SP001). Above this temperature SP001 also shows very low resistance; hence exceeding the safe current limit. The sample with 57% Al fraction (SP003) shows the highest TCR value of $8.1 \pm 0.4\%$ K^{-1} at 140 K. Additionally, the SP003 sample also shows a TCR of $\sim 4 \pm 0.5\%$ K^{-1} at around room temperature. This value is 2 times of the TCR value of VO_x bolometers ($\sim$2% K^{-1}) [8]. This behavior (TCR vs Al%) implies a better TCR for samples with 100% Al (i.e. AlAs), but further studies are needed to confirm this conclusion.

The specially mounted sample has the same structure as SP003 (the sample with 57% Al fraction). The noise current density of this device structure at two different bias voltages at 300 K is shown in Fig. 2. The device shows flat white noise with a noise currant density $<10^{-22}$ A^2/Hz ($\sim 5 \times 10^{-17}$ V^2/Hz) at higher frequencies ($f > 1000$ Hz). The theoretical limit in the Johnson noise for a device with similar resistance is 1.4×10^{-23} A^2/Hz (2×10^{-17} V^2/Hz) calculated by Nyquist equation, where k_B is the Boltzmann constant, T is temperature (300 K) and R is the device resistance ($\sim$1.2 kΩ).

$$\frac{V_J(f)}{\sqrt{\Delta f}} = \sqrt{4k_B TR}, \quad \frac{I_J(f)}{\sqrt{\Delta f}} = \sqrt{\frac{4k_B T}{R}}$$

The noise power density is around 5×10^{-22} A^2/Hz ($\sim 8 \times 10^{-17}$ V^2/Hz) at the 10 Hz with 1 V bias ($\sim$0.7 mA) for the GaAs/AlGaAs (SP003) bolometer. This noise spectral density is very low compared to noise values reported for different materials including Si ($\sim 4 \times 10^{-12}$ V^2/Hz at 1 Hz), VO_x ($\sim 10^{-12}$ V^2/Hz at 0.1 Hz) and Ge/Si ($\sim 7 \times 10^{-13}$ V^2/Hz at 250 Hz) alloy [6,9]. Inset to Fig. 2 shows the noise spectra after baseline correction. It shows $1/f$ noise dominating over the Johnson noise at low frequencies in the device.

The measured response spectrum of the specially mounted sample is given in Fig. 3. It shows a wavelength independent (flat) response as expected for a bolometer. With a 2.25 V bias across the top and bottom contacts, the device shows a detectivity (D^*) of $\sim 1.7 \times 10^6$ Jones, with a responsivity of $\sim$3.7 mA/W at 10 μm, operating at room temperature. The 2.25 V is the maximum safe bias voltage that can be applied to the device. The *IV* characteristic curve shows a drastic increase in the dark current in the device, due to Joule heating, just above this voltage. The response peak appearing in the range 2–6 μm is believed to be cause by inter band transitions (heavy hole, light hole and split-off hole bands) [10,11] due to photonic excitations of carriers. The response of the second structure is also showing a similar response, and the values lies within the uncertainty of measurements.

4. Conclusion

GaAs/AlGaAs multilayer heterojunction structures with different Al fractions and doping densities were tested for TCR values. Structures containing the p-doped GaAs emitter layers showed a better TCR compared to a similar heterojunction structure with n-doped emitters. Furthermore, a GaAs/AlGaAs multilayer structure with 57% Al fraction in the barrier layers showed a TCR value around 4% K^{-1}, at room temperature. This is a higher TCR value compared to that of VO_x or α-Si which is 2% and 2.8% respectively. Therefore with further research p-doped GaAs/AlGaAs heterostructures have the potential to be a competitive candidate in the future production of bolometers or microbolometers working at room temperature. Additionally, the device demonstrates a low noise spectral density, which is a requirement for good performance in a bolometer type detector.

Acknowledgements

This work was supported by the Georgia Research Alliance under GRAUP, USNSF under the grant # ECS-0553051, and the US Army Research Office under the grant # W911NF-08-1-0448 monitored by Dr. William Clark.

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