ІНФОКОМУНІКАЦІЙНІ ТЕХНОЛОГІЇ ТА ЕЛЕКТРОННА ІНЖЕНЕРІЯ
INFORMATION AND COMMUNICATION TECHNOLOGIES, ELECTRONIC ENGINEERING

№ 1 (1), 2021

STRAIN GAGES BASED ON GALLIUM ARSENIDE WHISKERS

A. Druzhinin, O. Kutrakov, I. Ostrovskii, N. Liakh-Kaguy, D. Chemerys
Lviv Polytechnik National University, 12, S. Bandery Str., Lviv, 79013, Ukraine

Corresponding author: Anatoly Druzhinin (e-mail: druzh@polynet.lviv.ua).

(Received 26 June 2021)

Strain-resistant properties of GaAs whiskers and ribbons of *p*- and *n*-type conductivity with various length (0.3–7 mm) and diameter (10–40 μm) have been investigated in a wide range of temperatures. Strain gages based on heavily doped *p*-type conductivity GaAs whiskers have linear deformation characteristics and a weak temperature dependence of strain sensitivity in the temperature range from –20 to +3500 °C. The temperature coefficient of resistance (TCR) of not fixed strain gages is about +(0.12–0.16) % × grad^{-1}. The temperature coefficient of strain sensitivity is –0.03 % × deg^{-1} in the temperature range –120+800 °C. Strain gages based on ***n***-type GaAs ribbons are characterized by high flexibility and high strain sensitivity. They are capable up to +4000 °C and can be used to measure deformations on curved surfaces at high temperatures. TCR of not fixed strain gages is –0.01 +0.03 % × grad^{-1}. The temperature coefficient of strain sensitivity is –0.16 % × deg^{-1} in the temperature range –120 ... +4000 °C.

Key words: *whiskers; ribbons; GaAs; strain gages; temperature coefficient of strain sensitivity; temperature coefficient of resistance*.

1. Introduction

Whiskers and ribbons of gallium arsenide are usually grown by various methods [1–4], in particular by chemical gas transport reactions in the GaAs-Br system. GaAs whiskers grow in the form of regular triangular or hexagonal prisms elongated in the crystallographic direction [111]. GaAs ribbons have a rectangular cross section and are elongated along the axis [211], they are twins in their structure. GaAs crystals, which are grown without special doping, have an electronic type of conductivity. Hole conductivity in these crystals is created during their doping with zinc during a growth. GaAs crystals grown in this way have a high mechanical value. Thus, GaAs whiskers with a diameter of 10 μm can withstand mechanical stresses of ~240 kg/mm^2, which corresponds to a deformation of $\varepsilon \approx 1.7$ %, for ribbons with a cross section of (0.016×0.34) mm^2 – 55 kg/cm^2. In addition, due to their shape, ribbons are very flexible – they can be bent in a radius of 4–6 mm.

The authors of [5–8] investigated the strain-resistant properties of GaAs crystals. The anomalous piezoelectric effect in GaAs nanowires was detected with the piezoelectric strain coefficient that is 12 times larger than the theoretically estimated value [7], which was explained by the dominant content of the phase with the wurtzite-type crystal structure and increased pressing forces from the contact layer. Thus, the investigation of the whisker and ribbons are very promising for comparison.

The present paper deals with studies of GaAs whisker and ribbon strain properties in a wide temperature range 0…300 ºC and deformations $\pm(1\times10^{-5}...\ 1\times10^{-3}$ rel. units). The GaAs whiskers have a thickness of 20–40 μm, a length of 4–7 mm, and ribbons with a width of 0.3–0.6 mm, a thickness of 10–15 μm, and a length of 3–6 mm. Contacts to such crystals were created by welding with gold microwire with a diameter of 20–30 μm.

2. Experimental results and their analysis

The dependences of the relative change in the resistance of GaAs whiskers with different resistivity on tensile deformation are showed in Fig. 1. The maximum value of the strain sensitivity for ***p***-type GaAs whiskers is K = +60 ÷ +64. It is worthy to note that ***n***-type GaAs whiskers have a low value of strain sensitivity (K≈–10). The obtained values of the longitudinal strain sensitivity coefficient K [11] for GaAs whiskers agree well with the value of the elastoresistance coefficient ***m*** [111], calculated through the piezoelectric coefficients for bulk GaAs crystals of ***p***-type [9] and ***n***-type [10–12] conductivity. It should be noted that for heavily doped ***p***-type GaAs whiskers (ρ = 0.001–0.004 Ohm×cm) a linear dependence of the relative change in resistance on deformation occurs (see Fig. 1).

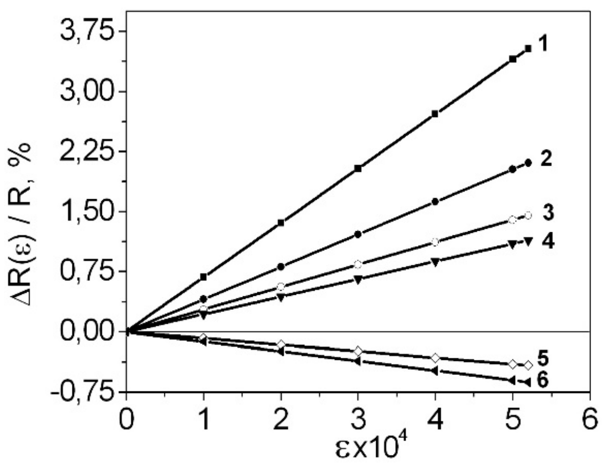


Fig. 1. Dependence of relative change of resistance for GaAs whiskers with different resistivity on tensile deformation: p-type: 1 – ρ = 0.1 Ohm×cm; K = 62; 2 – ρ = 0.003 Ohm×cm; K = 39; 3 – ρ = 0.0016 Ohm×cm; K = 26.7; 4 – ρ = 0.001 Ohm×cm; K = 21.7; n-type: 5 – ρ = 0.004 Ohm×cm; K = –9; 6 – ρ = 0.02 Ohm×cm; K = –11

During the study of strain gauge characteristics of gallium arsenide ribbons interesting results were obtained. If the values of the longitudinal strain sensitivity coefficient for ***p***-type GaAs ribbons (*K* = 33÷42) coincide with the calculated values of the strain-sensitivity coefficient in the [211] direction, then there is no such agreement for ***n***-type ribbons. The strain sensitivity of such crystals turned out to be higher than for ***p***-type ribbons and even higher than the strain sensitivity of ***p***-type conductivity GaAs whiskers. The strain sensitivity coefficient of the ***n***-type conductivity GaAs ribbons with a resistivity ρ = 0.005–0.12 Ohm×cm is –60 ÷ –107 (Fig. 2). The high values of the strain sensitivity are difficult to explain on the basis of the structure of the conduction band of gallium arsenide for ***n***-type GaAs ribbons. This may be due to the uneven distribution of impurities in the volume of such crystals during their growth.

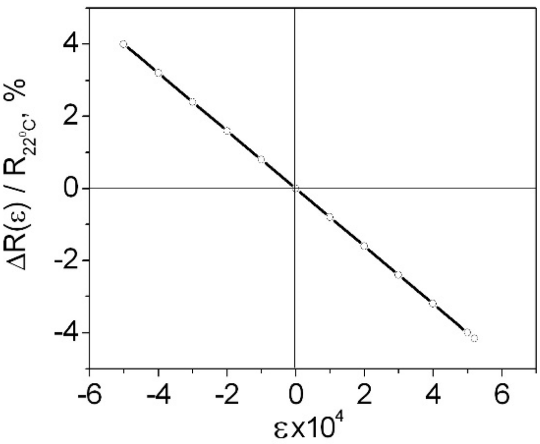
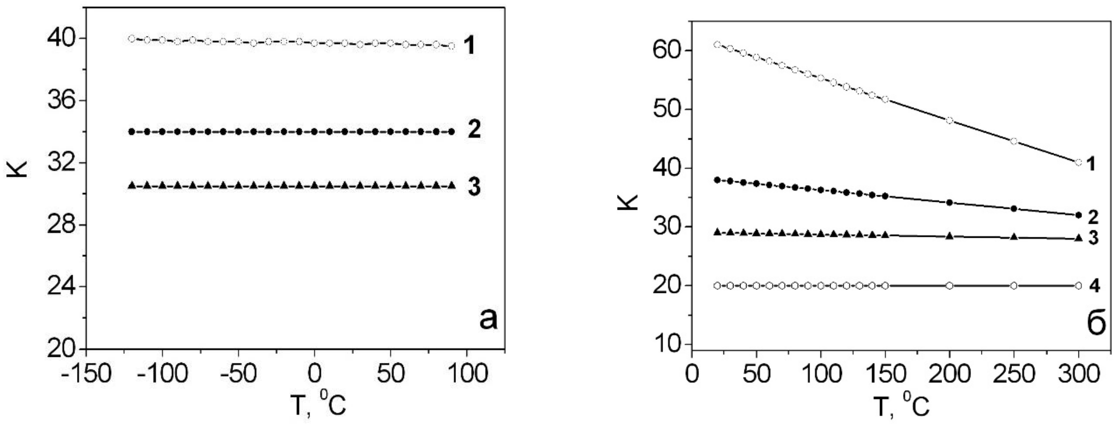


Fig. 2. Dependence of relative change in resistance of n-type GaAs ribbons (ρ = 0,008 Ohm×cm) on deformation

Tenzometric characteristics of GaAs crystals were studied in a wide temperature range –120 ÷ +350 °C. For free (unfixed) ***p***-type conductivity GaAs whiskers with a resistivity of 0.001–0.003 Ohm×cm there is almost a linear dependence of resistance on temperature, for such crystals TCR is +(0.10÷0.16) % × grad^{-1}. Repeated cycles of heating-cooling from +20 to +350 °C do not lead to significant changes in the resistance and temperature dependence of the resistance of these crystals, the change in resistance of the crystals does not exceed 1 %. The change in resistance of ***p***-type GaAs whiskers at long isothermal exposure (4–5 hours), at fixed temperatures +100 °C, +200 °C and +300 ºC does not exceed 0.4 %. Since the coefficient of strain sensitivity of high-alloy *p*-type conductivity GaAs whiskers is small, after fixing on a steel beam, the resistance and temperature coefficient of the resistance of these crystals changes slightly. Temperature dependences of the strain sensitivity coefficient for ***p***-type conductivity GaAs whiskers with different resistivity are shown in Fig. 3. As can be seen from the figure, the strain sensitivity for heavily doped crystals is very weakly depended on temperature over a wide temperature range. Thus, for ***p***-type GaAs whiskers with a resistivity of 0.001–0.002 Ohm×cm temperature sensitivity coefficient is –(0.02÷0.03)) % × grad^{-1} in the temperature range from –120 to +350 ºC. For these crystals, the linear dependence of the relative change in the resistance on deformation (at $\varepsilon = \pm\ 1\times10^{-3}$ relative units) is maintained over the entire temperature range from –120 to +250 °C.



а *б*

Fig. 3. Temperature dependence of the strain sensitivity coefficient of p-type conductivity of GaAs whiskers with different resistivity: a – fixed on steel with BC-10T glue (1 – 0.005 Ohm×cm; 2 – 0.003 Ohm×cm; 3 – 0.002 Ohm×cm); b– fixed on steel with BH-15T cement (1 – 0.1 Ohm×cm; 2 – 0.003 Ohm×cm; 3 – 0.002 Ohm×cm; 4 – 0.001 Ohm×cm)

The temperature dependences of the relative change in the resistance of ***n***-type conductivity GaAs ribbons attached to a steel beam are shown in Fig. 4. There is a certain correlation between the value of the strain sensitivity and TCR: crystals with higher resistivity have higher strain sensitivity and a more pronounced temperature dependence of the resistance. At a temperature of + 300 °C, the strain sensitivity of these crystals is ~ 50 % of its value at +20 ºC. With increasing temperature, the decrease in the strain sensitivity slows down, and in the temperature range +250 ÷ +450 ºC temperature dependence of the strain sensitivity for these crystals does not exceed –0.07 %×grad^{-1}. Reusable thermocycles in the temperature range +20 ÷ +400 ºC do not make significant changes in the value of resistance and its temperature dependence. The reproducibility of resistance for free ribbons in this temperature range is not worse than 1 %; the strain sensitivity of these crystals also does not change its value.

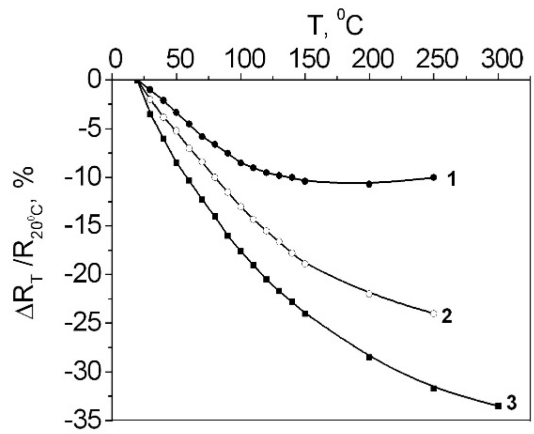


Fig. 4. Temperature dependence of the relative change in the resistance of the n-type conductivity GaAs ribbons with various resistivity, fixed on the steel with cement BH-15T: 1 – 0.08 Ohm×cm; 2 – 0.10 Ohm×cm; 3 – 0.12 Ohm×cm

Therefore, strain gages based on heavily doped ***p***-type conductivity GaAs whiskers are capable in a wide temperature range from –120 to + 350 °C, have linear deformation characteristics and a weak temperature dependence of strain sensitivity. Strain gages based on ***n***-type GaAs ribbons are characterized by high flexibility and high strain sensitivity. They are capable of up to + 400 ºC and can be used to measure deformations on curved surfaces at high temperatures. The main parameters of the developed strain gages are given in table.

Parameters of strain gages based on gallium arsenide whiskers

Parameter	Strain gages based on *p*-type GaAs whiskers	Strain gages based on *n*-type GaAs whiskers
Deformation range, relative units	±(1×10^{-5}... 1×10^{-3})	±(1×10^{-5}... 1×10^{-3})
Specific resistance, Ohm×cm	0.002–0.003	0.07–0.10
Resistance at 200 °C, Ohm	20–100	200–600
Coefficient of strain sensitivity at 200 °C	+30 ... +40	–75 ... –90
TCR of not fixed strain gages, % × grad^{-1}	+(0.12 – –0.16) in the range –60 ... +1800 °C	–0.01 ... +0.03 in the range +20 ... +2000 °C
Temperature coefficient of strain sensitivity,% × grad^{-1}	–0.03 in the range –120 ... +800 °C	–0.16 in the range +20 ... +3000 °C
Operating temperature range, °C	–120 ... +350	+20 ... +400
Maximum temperature, °C	+350	+450
Dimensions, mm	(0.02–0.04)×(0.02–0.04)×(4–6)	(0.3–0.5)×(0.005–0.015)×(3–6)

3. Conclusions

Tenzometric characteristics of GaAs whiskers and ribbons were studied in a wide temperature range –120 ÷ +350 °C. For free (unfixed) ***p***-type conductivity GaAs whiskers with a resistivity of 0.001–0.003 Ohm×cm there is almost a linear dependence of resistance on temperature, for such crystals TCR is +(0.10÷0.16) % × grad^{-1}. Repeated cycles of heating-cooling from +20 to +350 °C do not lead to significant changes in the resistance and temperature dependence of the resistance of these crystals, the change in resistance of the crystals does not exceed 1 %. The change in resistance of ***p***-type GaAs whiskers at long isothermal exposure (4–5 hours), at fixed temperatures +100 °C, +200 ˚C and +300 °C does not exceed 0.4 %. For ***p***-type GaAs whiskers with a resistivity of 0.001–0.002 Ohm×cm temperature sensitivity coefficient is –(0.02÷0.03)) % × grad^{-1} in the temperature range from –120 to +350 °C. For these crystals, the linear dependence of the change in resistance on deformation (at $\varepsilon = \pm 1\times10^{-3}$ relative units) is maintained over the entire temperature range from –120 to +250 °C.

At a temperature of +300 °C, the strain sensitivity of ***n***-type conductivity GaAs ribbons is ~50 % of its value at +200 °C. With increasing temperature, the decrease in the strain sensitivity slows down, and in the temperature range +250 ÷ +450 °C temperature coefficient of strain sensitivity for these crystals does not exceed –0.07 % × grad^{-1}. Reusable thermocycles in the temperature range +20 ÷ +400 ˚C do not make significant changes in the value of resistance and its temperature dependence. The reproducibility of resistance for free ribbons in this temperature range is not worse than 1 %; the strain sensitivity of these crystals also does not change its value.

References

[1] Dubrovskii V. G., Soshnikov I. P., Sibirev N. V., Cirlin G. E., Ustinov V. M. Growth of GaAs nanoscale whiskers by magnetron sputtering deposition, Journal of crystal growth, 289(1), (2006), 31–36.

[2] Borgström M., Deppert K., Samuelson L., Seifert W. Size-and shape-controlled GaAs nano-whiskers grown by MOVPE: a growth study, Journal of crystal growth, 2004, 260(1–2), 18–22.

[3] Metaferia W., Schulte K. L., Simon J., Johnston S., Ptak A. J. Gallium arsenide solar cells grown at rates exceeding 300 µm h^{-1} by hydride vapor phase epitaxy, Nature communications, 2019, 10(1), 1–8.

[4] Ohlsson B. J., Björk M. T., Magnusson M. H., Deppert K., Samuelson L., Wallenberg L. R. Size-, shape-, and position-controlled GaAs nano-whiskers, Applied Physics Letters, 2001, 79(20), 3335–3337.

[5] Dong B., Zaghloul M. E. Generation and enhancement of surface acoustic waves on a highly doped p-type GaAs substrate, Nanoscale Advances, 2019, 1(9), 3537–3546.

[6] Lee H. J., Look D. C. Hole transport in pure and doped GaAs, Journal of applied physics, 1983, 54(8), 4446–4452.

[7] Lysak V., Soshnikov I. P., Lahderanta E., Cirlin G. E. Piezoelectric effect in GaAs nanowires: Experiment and theory, Physica status solidi (RRL)-Rapid Research Letters, 2016, 10(2), 172–175.

[8] Donmez O., Sarcan F., Erol A. Determination of the acoustic phonon-hot carriers interaction in n-and p-type modulation-doped GaInNAs/GaAs quantum wells, Physica B: Condensed Matter, 2021, 612, 412946.

[9] Zhou J., Wu M. W. Spin relaxation due to the Bir-Aronov-Pikus mechanism in intrinsic and p-type GaAs quantum wells from a fully microscopic approach, Physical Review B, 2008, 77(7), 075318.

[10] Long Y., Huang J. Z., Wei Z., Luo J. W., Jiang X. OFF Current Suppression by Gate-gontrolled Strain in The N-type GaAs Piezoelectric FinFETs, In 2019 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), pp. 1–4. IEEE (2019, September).

[11] Zhou J., Cheng J.L., Wu M.W. Spin relaxation in n-type GaAs quantum wells from a fully microscopic approach, Physical Review B, 2007, 75(4), 045305.

[12] Hsu Y. W., Lu S. S., Chang P. Z. Piezoresistive response induced by piezoelectric charges in n-type GaAs mesa resistors for application in stress transducers, Journal of applied physics, 1999, 85(1), 333–340.

ТЕНЗОРЕЗИСТОРИ НА ОСНОВІ НИТКОПОДІБНИХ КРИСТАЛІВ АРСЕНІДУ ГАЛЛІЮ

А. Дружинін, О. Кутраков, І. Островський, Н. Лях-Кагуй, Д. Чемерис
Національний університет "Львівська політехніка", вул. С. Бандери, 12, Львів, 79013, Україна

Досліджено деформаційні властивості ниткоподібних і стрічкових кристалів GaAs *p*- та *n*-типів провідності із різною довжиною (0,3–7 мм) і діаметром (10–40 мкм) у широкому інтервалі температур. Тензорезистори на основі сильнолегованих ниткоподібних кристалів GaAs *p*-типу провідності мають лінійні деформаційні характеристики і слабку температурну залежність тензочутливості в інтервалі температур від –120 до +350 °С. Температурний коефіцієнт опору (ТКО) незакріплених тензорезисторів досягає +(0,12–0,16)%×град$^{-1}$, а температурний коефіцієнт тензочутливості в інтервалі температур –120 +80 °С становить –0,03 % × град$^{-1}$. Тензорезистори на основі стрічкових кристалів GaAs *n*-типу провідності відрізняються великою гнучкістю і високою тензочутливістю. Вони дієздатні до температур +400 °С і можуть використовуватись для вимірювання деформацій на криволінійних поверхнях за високих температур. ТКО таких незакріплених тензорезисторів становить –0,01 +0,03 %×град$^{-1}$, а температурний коефіцієнт тензочутливості в інтервалі температур –120 ... +400 °С досягає –0,16 % × град$^{-1}$.

Ключові слова: *ниткоподібні кристали; стрічкові кристали; GaAs, тензорезистори; температурний коефіцієнт тензочутливості; температурний коефіцієнт опору.*