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Electrical characteristics of semiconductor film structures obtained on a flexible substrate

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Abstract. In the frame of this work the current-voltage characteristics of thin films of polycrystalline silicon on a flexible polymer substrate were studied, measured when the film was bent in both tension and compression modes. The samples were fabricated by laser-stimulated metal-induced crystallization of amorphous Si films, deposited by magnetron sputtering on a flexible polyimide film both in constant power and pulsed mode. It has been established that the resistance of a polycrystalline Si film depends on the degree and type of deformation. The change in electrical resistance can be associated with an increase and decrease in the intergranular distance when the film is stretched and compressed, respectively. The resulting films are promising for the fabrication of semiconductor strain sensors and active elements of flexible electronics

Keywords: crystallization of amorphous silicon, metal-induced crystallization, laserstimulated crystallization, infrared laser radiation, flexible electronics

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Электрические характеристики полупроводниковых пленочных структур, полученных на гибкой подложке

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Аннотация. В рамках данной работы были исследованы вольт-амперные характеристики тонких пленок поликристаллического кремния на гибкой полимерной подложке, измеренные при изгибе пленки как в режиме растяжения, так и в режиме сжатия. Образцы были изготовлены методом лазерно-стимулированной металл-индуцированной кристаллизации аморфных пленок Si, нанесенных методом магнетронного распыления на гибкую полиимидную пленку. Установлено, что сопротивление пленки поликристаллического кремния зависит от степени и вида деформации. Изменение электрического сопротивления может быть связано с увеличением и уменьшением межзеренного расстояния при растяжении и сжатии пленки, соответственно. Полученные пленки перспективны для изготовления полупроводниковых тензодатчиков и активных элементов гибкой электроники.

Ключевые слова: кристаллизация аморфного кремния, металл-индуцированная кристаллизация, лазер-стимулированная кристаллизация, инфракрасное лазерное излучение, гибкая электроника

Финансирование: Инновационный подход к формированию кристаллических кремниевых структур на гибких подложках с помощью лазер-стимулированной металл-индуцированной кристаллизации (Проект РНФ № 00047-22-23).

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Introduction

Over the past decades, flexible electronics have undergone significant development due to its wide range of applications in various fields, including telecommunication systems, medicine, sensors, wearable devices, etc. [1–4]. An important problem in flexible electronics is the deposition of polycrystalline semiconductor thin films on flexible polymer substrates, which have a melting temperature lower than the crystallization temperature of semiconductor materials. In [5] reports a new method for the crystallization of thin silicon films, combining the advantages of laser and metal-induced crystallization technologies, which makes it possible to fabricate a polycrystalline silicon film on a flexible polyimide substrate. However, the stability of the electrical characteristics of polycrystalline films synthesized by this method on a polyimide film during its deformation has not previously been studied.

Therefore, the purpose of this work is to study the current-voltage characteristics (I–V curves) of thin films of polycrystalline silicon obtained by laser-stimulated metal-induced crystallization, measured when the film is bent in both tension and compression modes.

Materials and Methods

The samples were fabricated by magnetron sputtering of an amorphous silicon (*a*-Si) layer with 1 μm tick onto a 0.5-mm-thick polyimide substrate, followed by a layer of tin. Sputtering was carried out in a Nexdep installation (Angstrom Engineering, Canada), equipped with two magnetron sources with disk targets with a diameter of 76 mm. The residual pressure in the chamber was $2 \cdot 10^{-5}$ Torr. Argon was filled into the chamber until the operating pressure was $3.4 \cdot 10^{-3}$ Torr. Two samples were formed, differing in the silicon deposition mode. In the first case, silicon deposition occurred in direct current mode (constant mode, CM), in the second in pulsed mode with a frequency of 25 kHz and duty cycle of 75% (pulse mode, PM). Thus, two variants of a thin-film structure were obtained on a flexible polymer substrate, consisting of a 1-μm-thick silicon layer deposited directly on the polyimide substrate and a 40-nm-thick tin layer on top of the silicon. The power of the silicon magnetron source during the deposition process stabilized at the level of 500 W, the metal one at the level of 300 W. The thickness of the sprayed layers was controlled using piezoquartz sensors installed in a vacuum chamber and a digital spraying rate control system (Sycon, USA).

The resulting structures were processed on a MiniMarker-2 machine (Laser Center, Russia), equipped with a pulsed fiber laser with a wavelength of 1064 nm. Laser processing was carried out at the pulse energy was $1 \cdot 10^{-5}$ J, a pulse repetition rate of 200 kHz and a laser beam speed of 1200 mm/s. The duration of the pulse was 14 ns. Thus, the metal film served simultaneously as a laser radiation absorption layer and a crystallization inductor. A laser spot diameter is 20 μm. Since the distance between pulses is less than the diameter of the laser spot, these scanning parameters make it possible to obtain evenly crystallization of silicon over the entire treatment area. The presence of the crystalline phase was confirmed by the method of Raman's spectroscopy using the InVia (Renishaw, Great Britain). The spectrometer has a laser with a wavelength of 532 nm, a laser power up to 0.01 mW, a lens with a 50-fold increase. The obtained samples were studied by atomic force microscopy (AFM) by NTEGRA Spectra (NT-MDT Spectrum Instruments, Russia).

To realize the bending of the resulting films at a given angle, both in the stretching and compression modes, 3D printed equipment was manufactured that made it possible to secure two clamps. In this case, one clamp was stationary, and the second could be moved around the circle (Fig. 1).

Current-voltage characteristics (I–V curves) were measured using a probe station and an

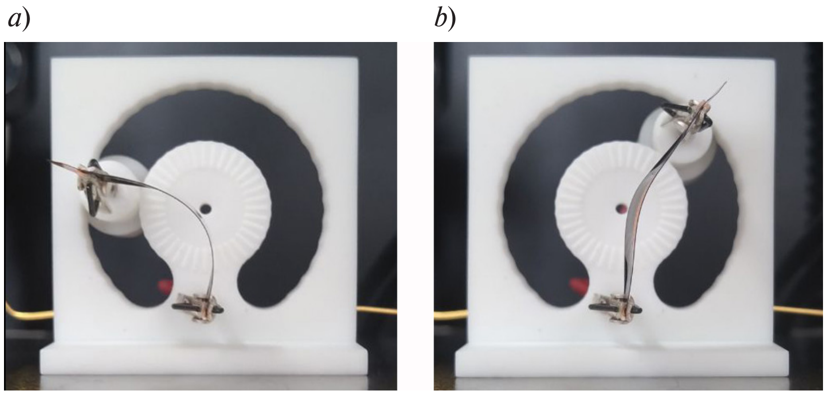

Fig. 1. Implementation of tension (*a*) and compression (*b*) modes of a polycrystalline silicon film on a flexible substrate when it is bent at a given angle

Agilent B1500a semiconductor device analyzer.

Results and Discussion

Fig. 2 shows AFM-images for the surface of an amorphous silicon film obtained both in constant and pulsed mode. From each AFM image, the surface roughness and average grain size were determined. Amorphous silicon films obtained in constant mode have an average surface roughness of 1.440.79± nm. For films fabricated in a pulsed mode, the average surface roughness is lower: 0.95±0.64 nm. Moreover, these films have a larger average grain size (52.98 nm) than that of films obtained in constant mode (32.73 nm). Laser processing of films with Sn layer leads to a hundredfold increase in surface roughness, regardless of the mode of obtaining the amorphous silicon film.

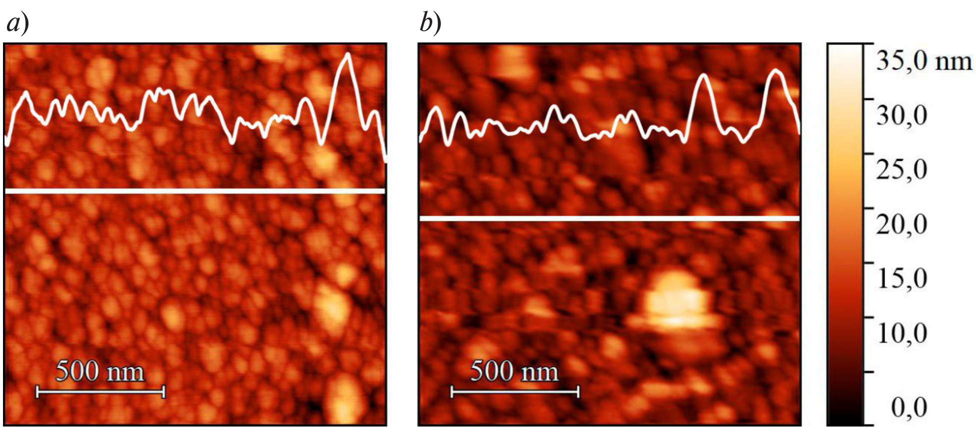

Fig. 2. AFM-images of studied amorphous silicon films on flexible polyimide substrate, obtained in constant power mode (*a*) and in pulsed mode (*b*)

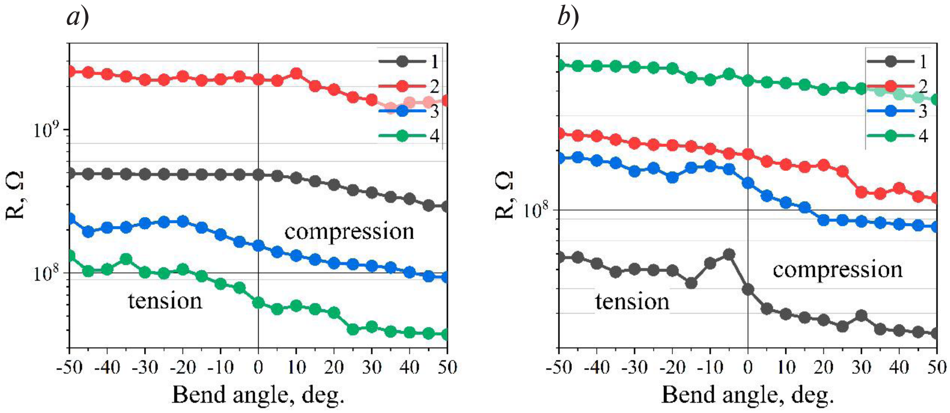

Fig. 3. Influence of bending on resistance of thin Si films: silicon films deposited at constant mode (*a*); silicon film was deposited at pulsed mode (*b*); bare silicon film *1*; Si film after laser treatment *2*; Si film with Sn layer *3*; Si film with Sn layer after laser processing *4*

The *I*–*V* curves of amorphous silicon films are linear, while curves of polycrystalline silicon films are nonlinear. When the film is bent in tension mode, its conductivity decreases, and when it is bent in compression mode, it increases. Moreover, the resistance of amorphous silicon films changes nonmonotonic with increasing bending angle. Fig. 3 shows the effect of Si film bending on its resistance after laser-stimulated metal-induced crystallization.

When the film is stretched, its resistance is on average $1.57 \cdot 10^9$ Ω, and when compressed it is $5.26 \cdot 10^7$ Ω. Such changes may be associated with an increase and decrease in the intergranular distance when the film is stretched and compressed, respectively.

The resistance of pure amorphous silicon films is poorly dependent on the bending angle. After laser processing, the resistance increases by an order of magnitude. This change can be associated with a predominance of ablation, which leads to thinner film and therefore to greater resistance. Also, this change can occur due to an increase in the density of defects caused by laser radiation. Adding a metal layer over a layer of amorphous silicon predictably leads to an increase in conductivity, and laser processing increases the conductivity even more. This change is associated with significant crystallization of the silicon film, which is confirmed by the data of AFM and Raman spectroscopy. Analysis of changes in the resistance of Si films obtained in pulsed mode requires additional comprehensive studies of the chemical and phase composition, for example, by methods of secondary ion masses of spectrometry and X-ray analysis.

Conclusion

Thus, thin films of polycrystalline silicon were obtained on a flexible substrate. It was found that the film resistance depends on the degree and type of deformation, therefore these films are promising for the fabrication of semiconductor strain sensors and active elements of flexible electronics.

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