сти. Это подтверждает высокое качество поверхности и достаточно высокую равномерность нанесения покрытий.

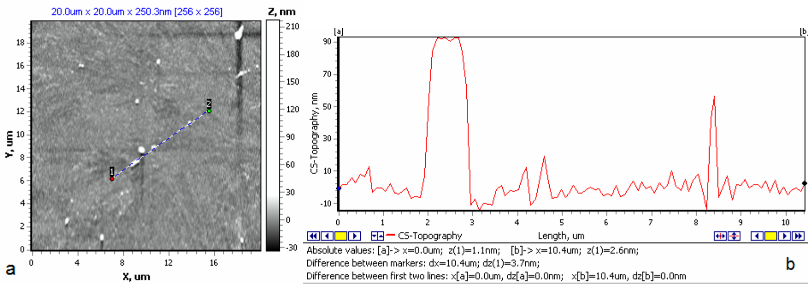

Рис.2. Топография поверхности (a), профиль сечения вдоль линии 1-2 (b) пленки композита GaSb-CrSb.

Заключение. Изучены микроструктура, рельеф поверхности тонких пленок полупроводникового эвтектического композита GaSb-CrSb. При помощи АСМ проведена оценка толщины нанесенного покрытия 0.8-0.9 мкм, что согласуется с ранее полученными данными. Низкая средняя шероховатость поверхности позволяет говорить о высоком качестве и равномерности наносимого покрытия.

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PROGRESS IN THIN-FILM $Cu_2ZnSnSe_4$ SOLAR CELLS

Photovoltaic (PV) is a very promising field amount various renewable energies. But solar cells can only establish themself durable on the market, if they are also economically profitable. Researchers PV is not only focusing on enhancing the conversion efficiency and the stability of the solar cells, but is also trying to find processes and technologies to reduce the costs. For example, flexible $Cu_2ZnSnSe_4$ (CZTSe) solar cells are very attractive and the many application possibilities compared with Si, CIGS and CdTe-based solar cells on glass substrates. The CZTSe is of interest because it has an optical direct energy bandgap (1.0 eV [1]) close to the ideal value for single junction solar cells. Also because of its direct energy bandgap, it has a high optical absorption coefficient, $\alpha > 10^4 cm^{-1}$ [1], resulting in the need for only a few microns of material to absorb most of the incident light. All of the constituent elements needed to make CZTSe, i.e., copper, zinc, tin, and sulfur, are highly abundant and therefore cheap, and all are environmentally acceptable [1].

Flexible solar cells offer several advantages for their manufacturing and applications compared to modules on glass substrates [2]. Solar cells on flexible substrates are very thin, light-weight and they can be applied on bendable surfaces, which makes them also more suitable in use. Another advantage of flexible substrates is the potential to use roll-to-roll technology for the production of thin films which lead to much faster payback of solar cells because of high throughput processing and low cost of the overall system.

In this paper, we briefly report evolution of growth technologies of CZTSe thin films on glass and flexibility metal substrates in a single report from their inception to the state-of-the-art development.

The evolution of efficiency of CZTSe solar cells using different deposition techniques of CZTSe thin films on different substrates is illustrated in Fig. 1. Several fabrication methods including vacuum-base, vacuum-free and solution process have been commonly used for CZTSe absorber layer deposition. The absorber layer fabrication techniques can be subclassified into one-step or two-step processes. Unlike CIGS, the vacuum-based CZTSe thin films fabrication technique had been exclusively the two-step process. Since the vacuum one-step steps are not so successful for the preparation of CZTSe thin films due to the volatility of tin, zinc, and selenium, which complicates their deposition on the substrate at high temperatures. It should be noted, that if the two-stage film production process uses a combination of vacuum and non-vacuum methods, the production costs could be additionally reduced. Recently, various non-vacuum methods have been applied to form precursors in the first step of the CZTSe films growth. Among these methods, electrochemical deposition is promising because of its low cost, easy to control, efficient use of materials, high throughput and nontoxic process.

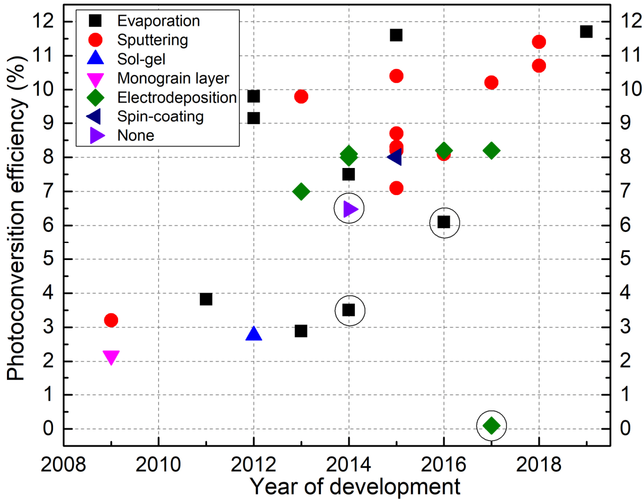

Figure 1 – Evolution of CZTSe-based solar cell efficiency using different deposition techniques and substrates [1,3–8]. The values circled correspond to the efficiency of thin-film CZTSe solar cells on a metal flexible substrates

The first thin-films CZTSe solar cells with efficiency of 3.2 and 2.16% reported in 2009 using a sputtering and a new type of device structure known as monograin layer (MGL) solar cell, respectively. Efficiency of the CZTSe thin-film solar cells has been improved significantly over the past decade since the first report in 2009. The best laboratory energy conversion efficiency 9.15 and 11.7 % has been achieved by CZTSe deposited using a one-step and two-step processes vacuum technique, respectively.

Metals and polymers are strong candidates as flexible substrate, but metallic foils offer the possibility to deposit the absorbing layer at temperatures similar or higher than those used for high-quality absorber on glass substrate. The Ti [4], SS [5,6], Mo [7–9], and Ta [2,9,10] foils have been used as substrates for CZTSe thin films. In 2014, for the first time CZTSe solar cells have been successfully grown on SS substrates with efficiency 6.1% [5]. In 2017, on Mo foil a record conversion efficiency of 6.48% has been achieved, which is the highest efficiency ever reported for CZTSe solar cell grown on metal foil [8].

So, thin film PV technologies are believing to be the most promising for terawatt scale PV deployment among the existing renewable energy technologies that could mitigate present as well as future energy crisis. Therefore, extensive research efforts must be given to increasing the efficiency of thin-films CZTSe solar cells for popularization as well as for viable commercialization.

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ИССЛЕДОВАНИЕ ФАЗОВОГО И ХИМИЧЕСКОГО СОСТАВА ПРЕКУРСОРОВ ZnS/Sn/Cu ДЛЯ ПОЛУЧЕНИЯ ТОНКИХ ПЛЕНОК $Cu_2ZnSn(S,Se)_4$

Введение. Благодаря своим оптическим и электрическим свойствам тонкие пленки $Cu_2ZnSn(S,Se)_4$ (CZTSSe) являются перспективными для