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Electrochemical deposition of contact materials for GaSb-based high-power photovoltaic converters

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The influence of the material, thickness and growth condition of the conductive contact layer on the morphology of contact bars, fill factor and efficiency of the GaSb-based photovoltaic converter is investigated.

Keywords: ohmic contact, conductive layer, electrochemical deposition, photovoltaic converter.

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Increasing attention is currently being paid to the post-growth formation of ohmic contacts to semiconductor devices, including those based on GaSb. The quality of metallization is improved by selecting new materials [1–8], adjusting the conditions for formation and annealing of contacts [1–9], and analyzing their degradation under external influences [10–14]. The thickness of ohmic contacts needs to be increased in order to reduce losses at the internal resistance of a high-power semiconductor device (specifically, a photovoltaic converter (PVC)), ensure high-quality bonding of external leads, and reduce their heating by the flow of high-density currents. Deposition with LOR resists [8] is typically used for contacts with a thickness below $1\,\mu$m. At larger thickness values, the processing cost increases due to the consumption of a significant amount of expensive metals. It is preferable to form contacts with a thickness of $2-5\,\mu$m by deposition from plating solutions [13,14]. The current study is aimed at examining the applicability of such contact systems in PVC technology and the ways to improve them.

The procedure of fabrication of ohmic contacts to heavily doped gallium antimonide ($p^+ \geqslant 10^{19}\,\text{cm}^{-3}$) and the front surface of high-power PVCs obtained by zinc diffusion into a GaSb substrate [15] was optimized. At the stage of post-growth processing, a contact was formed by deposition off an adhesive (Cr, Ti, or Ni with a thickness of 10 nm) layer and a lower conductive layer of Au or Ag (200–300 nm). The formed contact (*1* in Fig. 1) was annealed in a hydrogen atmosphere at a temperature of $\sim 175^\circ$C, followed by increasing the thickness to $\sim 2-5\,\mu$m via electrochemical deposition of an upper conductive layer of gold or silver (*2* in Fig. 1). Gold was deposited at a temperature of $55-60^\circ$C from a cyanide gold plating solution, while silver was deposited at room temperature ($18-23^\circ$C) from a ferricyanide silver plating solution. A barrier layer of nickel ($0.1\,\mu$m) was formed on top of the conductive film to prevent contact penetration during assembly. In turn, nickel was protected from environmental factors by a thin inert surface layer of gold ($0.2\,\mu$m), which is not subject to oxidation even at high temperatures of a photocell.

The high quality of the ohmic contact and post-growth processing should be confirmed by:

— fine adhesion to the semiconductor structure;

— correspondence to the contact grid pattern and minimal lateral expansion of metallization;

— low surface roughness, integrity of deposited layers, and lack of voids both in the deposited metal films and at their heteroboundaries;

— high output PVC parameters (in particular, fill factor FF).

The electrochemical deposition of contact materials was carried out through a photoresist mask (*3* in Fig. 1) that ensured accurate reproduction of the specified device topology. Silver was deposited from the ferricyanide silver plating solution at room temperature, which made it possible to exclude photoresist hardening and obtain a layer with smooth side walls and sharp and precisely defined boundaries (Fig. 1, *c*). At the same time, the plasticity of deposited silver made it possible to form smooth walls of contact bars and achieve fine adhesion to the semiconductor material even with a film thickness of $5-6\,\mu$m. The surface morphology of contacts was investigated with a Camscan scanning electron microscope and a scanning stylus profilometer.

The use of the cyanide plating solution for gold deposition resulted in destruction of the photoresist mask under the influence of CN^- ions. This process may be suppressed via thermal hardening of the photoresist. However, hardening resulted in distortion of the side wall profile of the mask (Fig. 1, *a*), which has a negative effect on the accuracy of contact formation due to the expansion of gold into the photosensitive PVC region (*4* in Fig. 1, *b*). The table illustrates how the latter process evolves as the thickness of the conductive contact layer increases. It is worth emphasizing that the expansion of contact strips should be taken into account when one develops photolithography exposure masks: the window for a contact deposited from a plating solution must be smaller than the window for deposition. In the example given in the table, the strip

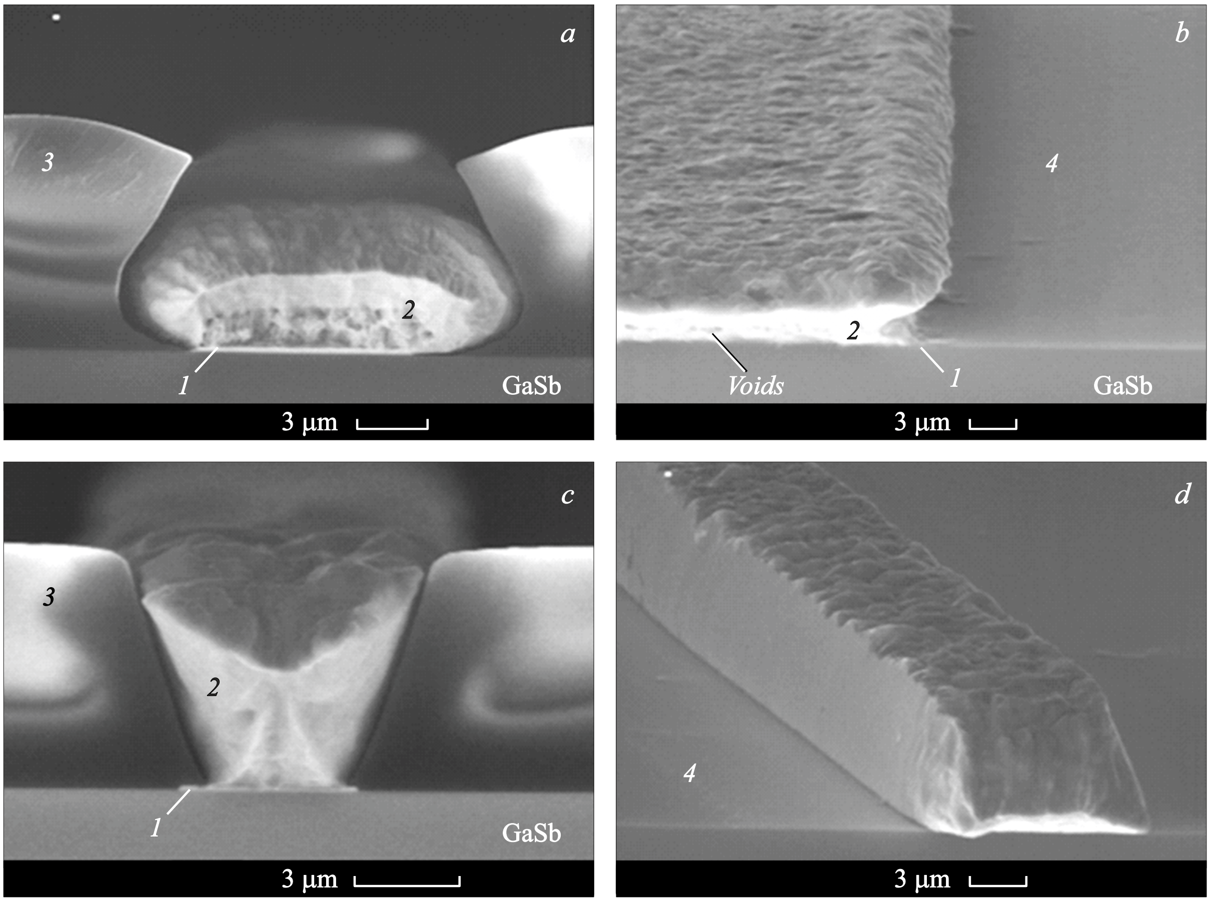

Figure 1. Micrographs of contact strips to GaSb-based PVCs formed by sputtering (*1*) and electrochemical deposition (*2*) of metal films. *a*, *b* — Conductive gold layer; *c*, *d* — conductive silver layer. *3* — Photoresist mask; *4* — photosensitive area.

Expansion of contacts deposited from plating solutions

Thickness of the conductive layer of the contact d, μm	Contact width, μm	Surface shading by strip contacts, %	Overall surface shading (by the peripheral bar and strip contacts), %
0.9*	8.2	4.0	42.8
1.2*	10.25	5.0	43.8
2.1*	10.7	5.2	43.5
3.1*	12.3	6.0	44.0
5.0**	14.3	7.0	44.6

* Contact with an Au conductive layer.

** Contact with an Ag conductive layer. The deposition was performed using a photoresist mask with a positive slope of the side wall.

widths specified by the exposure mask were 8 and 10 μm, respectively.

The electrochemical deposition of silver for the samples presented in Fig. 1, *c* was performed using a photoresist mask with a positive slope profile of the side wall. It is advisable to use masks with their side walls being vertical or having a negative slope in order to suppress the expansion of thick (5–6 μm) silver-containing contacts and reduce the degree of PVC shading. Smooth walls of contact bars are deposited in this case in strict accordance with the specified device topology, and the contact material does not penetrate into the photosensitive region of a chip (*4* in Fig. 1, *d*).

Gold contacts have an advantage over silver-containing ones in being highly inert, which is important for devices designed to operate in aggressive environments. A higher specific conductivity and lesser penetration of a contact into the depth of the semiconductor structure are among the advantages of silver over gold. The advantage of tempera-

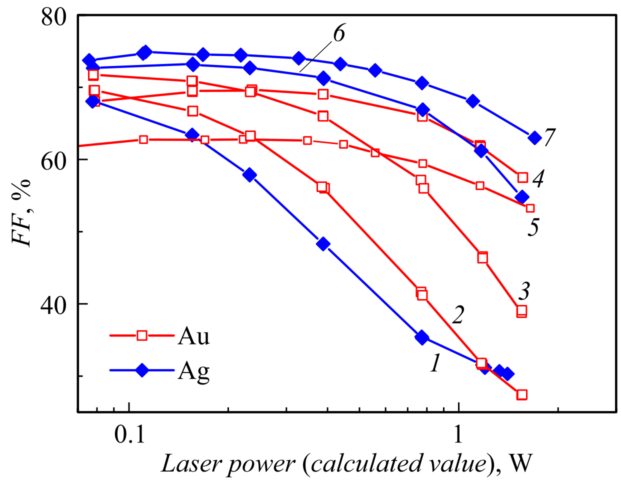

Figure 2. FF of photovoltaic converters of laser radiation with Ag (*1*, *6*, *7*) and Au (*2*–*5*) in conductive layers of the contact grid as function of the power of incident laser radiation with a wavelength of 1550 nm. Layer thickness d, μm: *1* — 1.4, *2* — 1.9, *3* — 2.5, *4* and *6* — 2.7, *5* — 3.6, and *7* — 5. Electrochemical deposition of silver was performed with a positive slope of the side wall of the photoresist.

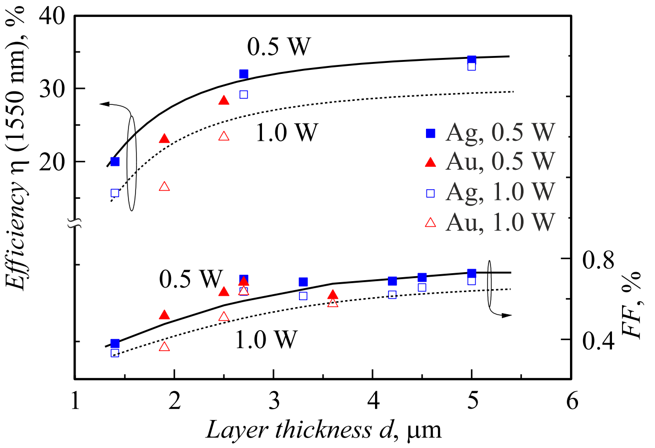

Figure 3. Variation of FF and the monochromatic ($\lambda = 1550$ nm) efficiency with thickness of the conductive layer of the front contact. The data for an incident laser power of 0.5 and 1.0 W are presented.

ture and temporal stability of silver-containing contacts over their gold-containing counterparts has been discussed earlier in [14]. In the present study, the focus is on determining the influence of contact thickness and material on fill factor FF and efficiency η of a laser radiation converter. With equal thickness of conductive films, the substitution of Au with Ag leads to a reduction in spreading resistance and, consequently, to an increase in FF (Fig. 2). The fill factor is presented as a function of the power of incident laser radiation with a wavelength of 1550 nm.

The ohmic losses of the PVC decrease with an increase in thickness of the conductive layer of both materials (Figs. 2 and 3). The critical FF reduction at gold thickness $d = 3.6\,\mu$m is to be associated with the mechanical deformation of thick films, which leads to partial separation of metallization from the semiconductor. Since silver has better plastic properties, the above phenomena are less pronounced. The adjustment of deposition modes made it possible to raise the conductive layer thickness to $5\,\mu$m while maintaining mechanical contact with the structure. Figure 3 illustrates the monotonic growth of FF to 73 and 69% with an increase in conductive layer thickness at incident radiation power levels of 0.5 and 1.0 W, respectively. As the contact grows in thickness from 3 to $5\,\mu$m, it expands in width by $\sim 2\,\mu$m, raising the shading losses by $\sim 1\%$. A further increase in metallization thickness appears to be impractical: the $FF\,(d)$ and $\eta\,(d)$ curves tend to saturation. The data presented in Figs. 2, 3 characterize the electrochemical growth of Au–Ni–Au or Ag–Ni–Au films on a pre-deposited Cr–Au contact grid with the use of a photoresist mask with a positive slope of the side wall. The highest values of monochromatic efficiency of such PVCs ($\eta = 33.5{-}34\%$ at a wavelength of 1550 nm) are achieved at a laser power below 1.0 W.

The morphology of silver-containing contacts (Fig. 1, *d*) may be improved in two-stage Ag deposition with an increase in current density from 0.005–0.01 to 0.04–0.05 mA/mm^2, horizontal positioning of the structure and the anode in the plating solution, and periodic vibration of the anode. The specifics of electrochemical deposition of Ag films were discussed in more detail in [16]. The formation of thick silver-containing contacts with a vertical wall profile should provide an opportunity to reduce the overall surface shading by more than 1.5% and raise the PVC efficiency.

Thus, the adjustment of electrochemical deposition modes makes it possible to increase the thickness of the conductive silver layer to $d = 5\,\mu$m while maintaining the adhesion of Ag–Ni–Au contacts to the semiconductor structure and high FF values ($\sim 73\%$ at a laser power of 0.5 W). The growth of silver layers thicker than $5\,\mu$m does not lead to any significant enhancement of FF and η and, consequently, is not advisable. The recommended thickness of a gold conductive contact layer is $\leqslant 3\,\mu$m, which is due to the risk of mechanical deformation and partial separation of metallization from the semiconductor.

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Conflict of interest

The authors declare that they have no conflict of interest.

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