Int. J. Nanoelectronics and Materials **8** (2015) 111-120

Transmission line method (TLM) measurement of (metal/ZnS) contact resistance

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Received 16 Nov. 2014; Revised 19 Jan. 2015; Accepted 29 Jan. 2015

Abstract

In this paper, we have examined different metals (Au, Al, In) Ohmic contacts on spray deposited ZnS thin films. The thermal stability of the contact structures was also examined by annealing process. Specific contact resistance was determined by characterizing the current-voltage relation from transmission line method (TLM) measurement. The electrical characterization shows that the (I-V) characteristics of the (metal/ZnS) contacts are fairly linear up to a certain value of the applied voltage. Except Au, the used metals show excellent Ohmic contact with ZnS films over a wide range of applied voltage. Specific contact resistance of (In/ZnS) films has been found to be of an order of magnitude lower than that of other metals. The lowest specific contact resistance of (5.2875 $\Omega.cm^2$) at room temperature for (In/ZnS) was obtained after annealing at (673 K) for 90 min, which confirmed the thermal stability of the contacts.

Keywords: ZnS; Spray Pyrolysis; Characterization.
PACS: 73.40.Lq; 81.15.Rs; 81.07.-b.

1. Introduction

Zinc sulfide (ZnS) is a semiconductor compound with large direct band gap; it is highly suitable for a number of optoelectronic device applications, such as solar cells, electroluminescent display, optical sensors, etc., although it is possible to prepare crystals of ZnS with relatively higher n-type conductivity. So, because of their possible technological applications, the study of ZnS thin films is quite important [1, 2].

Despite the progress on ZnS and its devices, there are several technological challenges in the fabrication of efficient devices. Among them, selection and development of compatible, low-resistance, and thermal stable Ohmic contacts to ZnS films is one of the crucial and challenging tasks [3]. An Ohmic contact is defined as a metal-semiconductor contact that has linear current-voltage (I-V) characteristics and also has a negligible contact resistance relative to the bulk or spreading resistance of the semiconductor. The development of zinc sulfide devices has the difficulty in forming Ohmic contact

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regions without simultaneously introducing large concentrations of defects which interfere with desired injection. Another major problem in electroding zinc sulfide stems mainly from its very low electron affinity and the very large energy barrier that exists between the zinc sulfide surface and metal contact interface [4, 5].

Metal/semiconductor contact is of great importance since it is required by semiconductor device to support communication with the outside world. An ideal Ohmic contact should not significantly perturb device performance, and it should be able to supply the required current without any applied voltage drop across the active region of the device. Depending on the characteristics of the interface, it can have either as a rectifying Shottky diode or as an Ohmic contact [3].

In order to realize the application of ZnS in power electronic devices, one of the most essential topics is to obtain a reliable Ohmic contact with the low specific contact resistance in the (metal/ZnS) interface. To identify such contacts to ZnS films, it is desirable to use elements which form intermetallic compounds easily with high melting points after the formation of Ohmic contact. The selected Ohmic contact should also have good adhesion, smooth surface, and lower metal sheet resistance. In general, Ohmic contact can be made with a n-type material by using a metal which acts as a donor in the crystal lattice. The metal contact whose work function is closer to ZnS work function and/or greater than the electron affinity of ZnS can establish Ohmic or nonrectifying junction with ZnS since their Fermi level exactly pins between conduction and valence bands [3, 6].

There are several ways to measure the Ohmic contacts in the metal/semiconductor interface, the most commonly used technique for measuring the contact resistance is the transmission line model (TLM) [6, 7]. In this paper, therefore, we report the electrical behavior of as grown and annealed (metal/ZnS) Ohmic contact structures and their thermal stability by using the transmission line model to measure the contact resistance and their specific resistivity. Thus, we have selected metals (Au, Al, In) as contacts that satisfies at least some of the above criteria.

2. Experimental procedure

2.1. Sample preparation

n-type ZnS thin films were prepared by the deposition process on cleaned glass substrates with the dimensions (76.2 mm × 25.4 mm × 1 mm) using spray pyrolysis technique under optimized deposition conditions, where it is noted that the ZnS films grown at a substrate temperature of 648 K with molar ratio in starting precursor solution of Zn:S = 1:2 showed enhanced crystallinity than that of the films grown at lower or higher substrate temperatures. The structure, the morphology and the stoichiometric of the films were confirmed by appropriate techniques including X-ray diffraction (XRD), scanning electron microscopy (SEM), atomic force microscopy (AFM) and the energy dispersive X-ray spectrum (EDX) analysis, as shown in Figure 1, where these analyses indicated that the best crystalline and stoichiometric films grown from a molar ratio of 1:2 solution is at a substrate temperature of 648 K. In order to evaluate the electrical properties of the films, the metal contacts (Au, Al, In) were deposited on ZnS films using thermal evaporation technique at a substrate temperature of 393 K under a high vacuum.

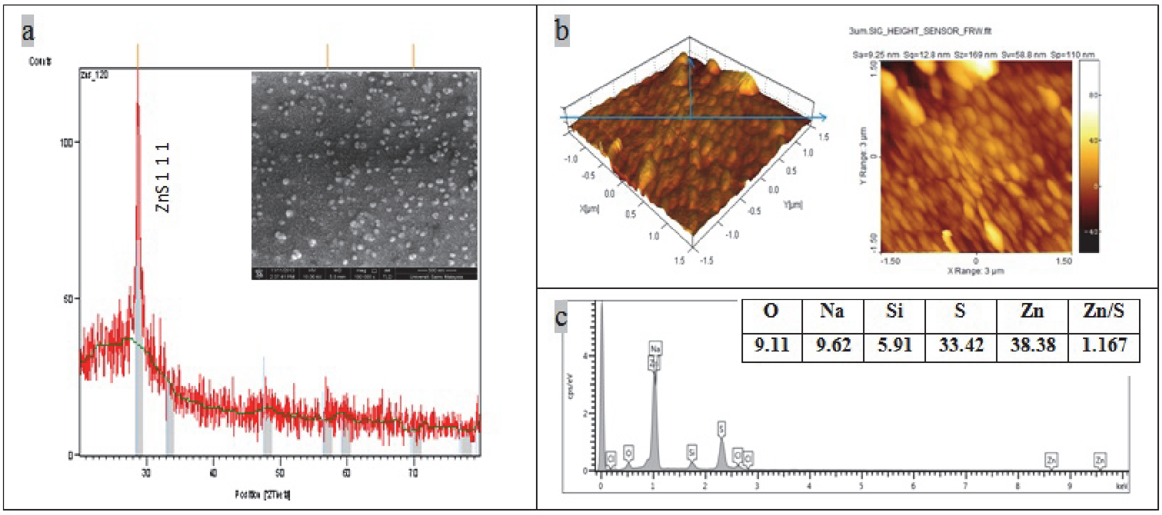

Fig. 1: a) XRD pattern, and inset SEM image, b) AFM 3D images, c) EDX spectrum of ZnS thin films deposited at a substrate temperature of 648 K with a molar ratio of precursor Zn:S = 1:2.

2.2 Measurement techniques

The current (I) and the voltage (V) of the ZnS structures were measured at room temperature under dark condition using two point probe method, where the current measured by a precise current meter (Picometer, Voltage source model Keithley 6487) through two successive contacts, keeping a fixed voltage across those contacts, as shown in Figure 2. Here, the total resistance (R_T) between the series metal electrode-semiconductor-metal electrode (R_{T1}, R_{T2}, R_{T3},...) was determined from the inverse slope of a linear fit of the (I-V) plot, and the Ohmic nature of the contacts was estimated from the value of the coefficient of determination (r^2) of the (I-V) plot, which would be 1 for an ideal Ohmic contact [8].

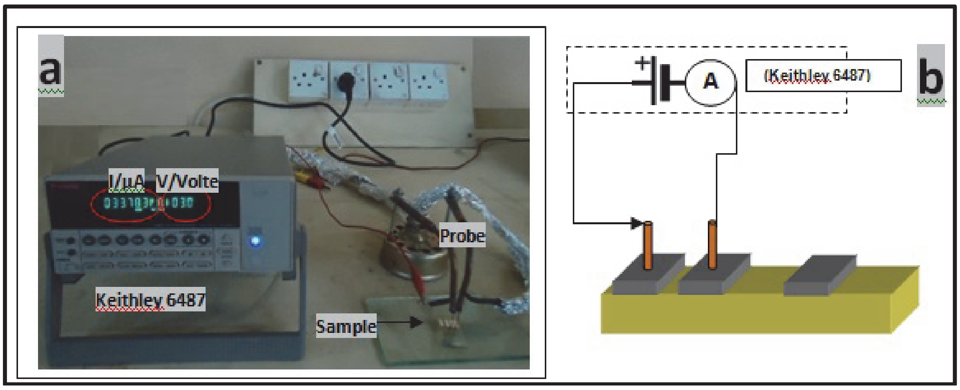

Fig. 2: (a) Photographic and (b) schematic diagram for the current and voltage measurements.

Contact resistance is a measure of the ease way with which current can flow across a metal semiconductor interface; the contact resistance (R_c) is measured using the transmission line method (TLM). The TLM test structure consists of several electrodes that exhibit with the same geometry of length (L) and width (W), (TLM) structure with the type of the mask used in the contact possess consists of several electrodes is shown in Figure 3 with length (L = 3 mm), width (W = 10mm) and different distances (d) between any two series electrodes, which measured microscopically for the used mask. The measurements of resistances are made between adjacent electrical contacts while the separation between the electrodes (d) is varied.

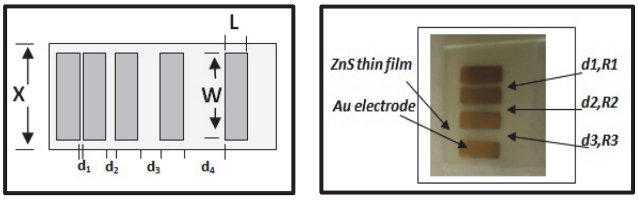

Fig. 3: a) A transmission line method test structure b) a photographic image of the mask used for In deposition on ZnS films.

The resistance values are plotted for different space distances between the electrodes, and linearly fitted to a graph, as shown in Figure 4.

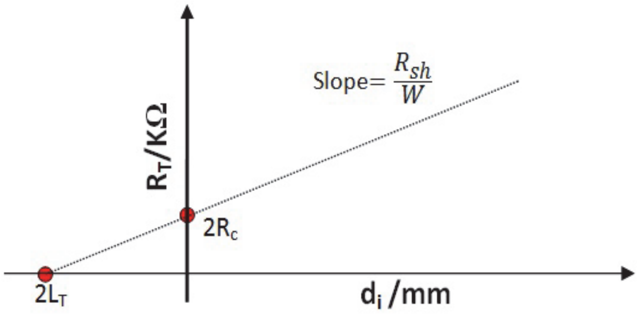

Fig. 4: Plots of total resistance versus contact spacing explain the (TLM) measurement technique.

From the plot of the total resistance as a function of the electrode spacing, four contact parameters can be extracted: sheet resistance (R_{sh}), contact resistance (R_c), specific contact resistance (ρ_c), and the current transfer length (L_T), where the current transfer length defined as the length of the contact used for transferring most of the current from the semiconductor to the metal or from the metal to the semiconductor [3], see Figure 5a.

When the current (I) is passed through the sample from the contact 1 to the contact 2, and the voltage (V) is measured across the two contacts, the total resistance, R_T = V/I, is given as [9]:

$$R_T = \frac{V}{I} = 2R_c + R_{semi} = 2R_c + R_{sh}\frac{d}{W}$$

Where R_{semi} is the resistance of the semiconductor layer, see Figure 5b

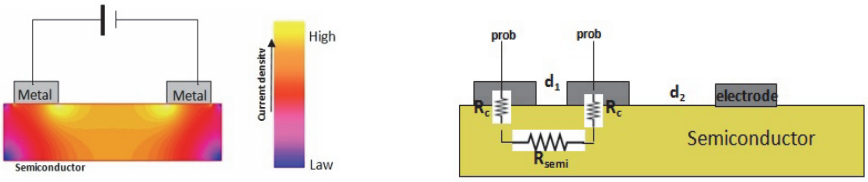

Fig. 5: a) A schematic diagram showing the contacts to a film layer, with the contact resistance and the film resistance indicated, b) Current density distribution in the lateral contact geometry.

When d = 0, the intercept with the ordinate is double the value of the contact resistance $2R_c$ (Ω).

$$R_T = 2R_c$$

Thus the transfer resistance:

$$R_t\ (\Omega.\text{cm}) = R_c \times W$$

The LTM analysis yields:

$$R_T = \frac{R_{sh}}{W}(d + 2L_T)$$

$$\text{At } d = 0 \qquad R_T = 2L_T\frac{R_{sh}}{W}$$

When $R_T = 0$, the intercept of linear fit with the x-axis is double the value of the current transfer length ($2L_T$).

$$d = 2L_T$$

Solving for R_{sh} (Ω per square) yields:

$$R_{sh} = \frac{R_c W}{L_T} = \text{slope} \times W$$

After calculating the sheet resistance of the semiconductor layer and the current transfer length of the metal semiconductor interface, the specific contact resistance ρ_c ($\Omega.\text{cm}^2$) can be determined according to the equation [4, 6]:

$$\rho_c = R_{sh} \times {L_T}^2$$

2.3 Thermal stability

One of the most important criteria for an Ohmic contacts is its thermal stability [10, 11]. To study the thermal stability of the Ohmic contacts to the (metals/ZnS) contact structures, the films were annealed at a temperature (673 K) in the air for 90 minutes by using a heater with Ceramic Top Hot Plate and K-type thermocouple connected to temperature control, where the contact deteriorated when the annealing temperature was higher than (673 K). Then, all the above measurements have been repeated for the contacts, resistance study of the annealed films, and the results were compared with those for un-annealed films.

3. Result and discussion

Figure 6 shows the (I-V) characteristics at room temperature corresponding to different spacing between two neighboring contacts of different metals (Au, Al, In) on ZnS films. The Ohmic nature of the contacts was estimated from the coefficient of determination (r^2) of the (I-V) plots, which would be 1 for an ideal Ohmic contact, thus we applied transmission line method (TLM) only for the contacts that have $r^2 \geq 0.99$.

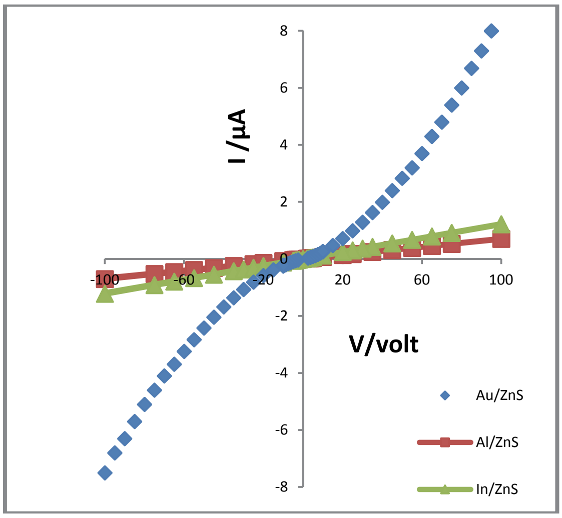

Fig. 6: I-V plots of (metal/ZnS) structures measured at room temperature.

It is clearly seen from Figure 6, except Au, the others two metal contacts with ZnS shows a linear (I-V) characteristic over the wide range of voltage varied from (-100 to 100V) which indicates good Ohmic contacts behavior with ZnS films since their $r^2 \geq 0.99$. However, the (I-V) plots for the (Au/ZnS) structure exhibited non Ohmic contact behavior even in low voltage range, as shown in the inset of Figure 6. So we determine the contact resistivity only for (In/ZnS) and (Al/ZnS) structures, where their coefficient of determination $r^2 \geq 0.99$. From Figure 6, it can also be noticed that the current flow through (In/ZnS) structures is high as compared to other structures. It indicates the (In/ZnS) structures have low electrical resistivity than that of other structures. These differences in the behavior of (metal/ZnS) structures might be attributed to the diffusion of metal ions into the ZnS crystal lattice and/or the formation of different intermediate binary and/or ternary phases between the metal and ZnS films, since the melting point for these metals is different [4, 7]. From the measured values of the total inter-electrode resistance (R_T) between any two neighboring electrodes for different values of the contact spacing (d) we draw (R_T - d) graph as shown in Figure 7.

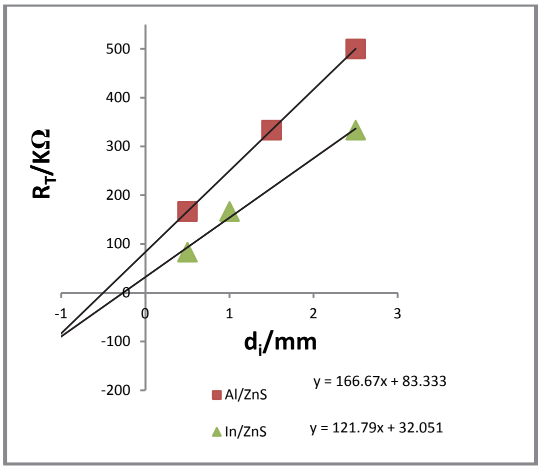

Fig. 7: Plots of the measured total resistance as a function of the contact electrode spacing.

The data show excellent linear relationships, from which we can calculate all the parameters for our Ohmic contacts study as; the current transfer length (L_T) and the contact resistance (R_c) can be calculated from the X and Y ordinate intercepts respectively, then the transfer resistance (R_t), the sheet resistance (R_{sh}), and the specific contact resistance (ρ_c) can be determined according to the relations explained in the measurement techniques given above [3, 7]. Figure 8 shows the (I-V) characteristics corresponding to different spacing between two neighboring rectangular electrode contacts of (Al/ZnS) and (In/ZnS) structures (annealed at 673 K in air for 90 min) at room temperature.

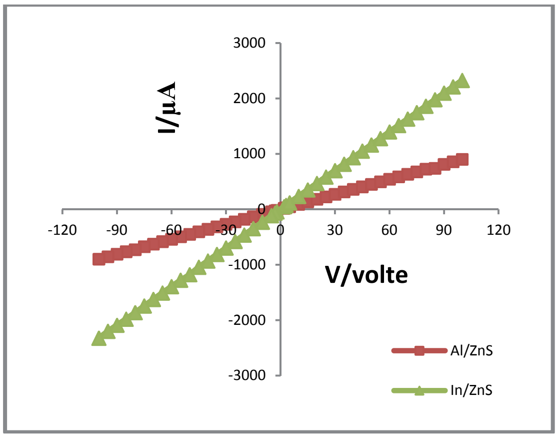

Fig. 8: I-V plots of annealed (metal/ZnS) structures measured at room temperature.

It is clearly seen that the annealing improved the linearity of (I-V) contacts characteristic, the structures exhibited a clear Ohmic behavior over the entire voltage range, from which we can deduce the total resistance between any two neighboring contact electrodes. It shows the total resistivity of (Al/ZnS) and (In/ZnS) structures decreased after annealing, on the other hand, the annealed structures displayed different trends in their (I-V) characteristics. The (I-V) plots of annealed (In/ZnS) structure shows good Ohmic nature. The inter-electrode resistances of the two contact structures are plotted as functions of spacing of the linear TLM contacts as shown in Figure 9, from which the contact parameters L_T, R_c, R_t, R_{sh}, and ρ_c for the two metal contact structures such as (Al/ZnS) and (In/ZnS) after annealing process were determined and the results are given in Table 1, compared with those for un-annealed contact structures.

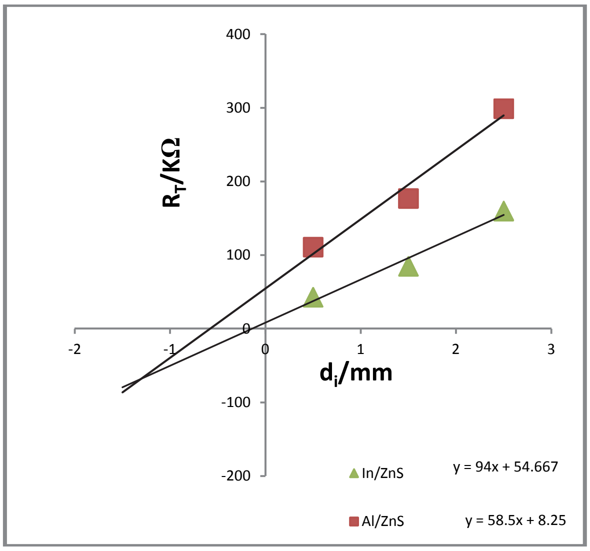

Fig. 9: Plots of the measured total resistance as a function of the contact electrode spacing after annealing process.

Table 1: The determined contact parameters for the metal contact structures before and after annealing process.

	r^2	R_c(KΩ)	L_T (mm)	R_t(KΩ.cm)	R_{sh}(KΩ.squre)	ρ_c (Ω.cm^2)
Au/ZnS	0.957765	**Non Ohmic**				
In/ZnS	0.999738	16.025	0.15	16.025	121.7	27.382
AL/ZnS	0.999384	41.665	0.25	41.665	166.6	104.12
				After Annealing		
In/ZnS	0.999524	27.33	0.075	27.33	94	5.2875
AL/ZnS	0.999704	4.125	0.29	4.125	58.5	49.198

Basically, the overall changes in the properties of annealed contact structures are probably attributed to the formation of intermetallic compounds and crystallinity of the films. A decrease in the resistivity of (metal/ZnS) structure can be attributed to the diffusion of metal atoms into the ZnS crystal lattice, improves the crystallinity of the ZnS film by neutralizing the defect states within the ZnS lattice that leads the electrical resistivity of the films to lower values. This may be an appropriate reason for the decrease in resistivity in (metal/ZnS) structure with annealing [8]. As a comparison, a drastic change in the electrical properties of (In/ZnS) structures with annealing temperature is due to the low value of In melting point (433 K).

It is observed that the specific contact resistance, for (In/ZnS) contacts is better in comparison with the other two metal contacts. The (In/ZnS) contacts show ρ_c value of (27.3825 Ω.cm^2) which is decreased by about four orders of magnitude from the value of ρ_c for (Al/ZnS) contacts (104.125 Ω.cm^2). On the other hand, after annealing at 673 K in air for 90 min, the (In/ZnS) contacts show ρ_c value of (5.2875 $\Omega.cm^2$) which is decreased by exactly ten orders of magnitude from that for (Al/ZnS) contacts (49.1985 $\Omega.cm^2$). Also, it can be seen from the above results of specific contact resistance, the (In/ZnS) contacts show ρ_c value decreases by more than five orders than that for its initial value, while specific contact resistance, for (Al/ZnS) contacts decreases to only half of its initial value before annealing.

Most of the thin film devices are working in the way that the electrical current is transferred laterally through the device. The case of lateral current transfer is typical for the solar cells and also in the case of thin film transistors. In the case of the homogeneous semiconductor layers, the current distribution under the electrical contact is not anymore uniformly distributed along the area below (or above) the electrical contact, because the current is choosing a less resistive path to travel through the semiconductor material. The highest current density occurs on the inner part of electrical contact, and reduces its value along the horizontal contact area [3, 7], as shown in Figure 5a.

Electrical contacts of devices with narrower electrodes exhibit higher values of the contact resistance. In order to minimize it, one has to come with a design of electrical contact with longer electrodes. The other way of minimizing electrical losses in the contacts is by minimizing the specific contact resistance parameter of the metal-semiconductor interface. With lower values of the specific contact resistance, the normalized contact resistance is reduced [3].

Returning to our constructed mask given in Figure 3, the way for accurate specific contact resistance ρc measurement is to ensure that the contact width (W) is wide enough to cover the entire width of the conducting strip X. If (W < X) lateral current crowding will result, this problem can be cover came by deposition electrodes with (W = X). The other way to accurately ρ_c is by decreasing the electrodes spacing d. So, we need to construct a mask with wider W and narrower d for that case.

4. Conclusion

In this paper, n-type ZnS films were deposited on cleaning glass substrates using a spray pyrolysis technique under optimized deposition conditions. Different elemental metals (Au, Al, In) were selected for Ohmic contacts and deposited on prepared ZnS thin films by thermal evaporation technique, and studied their physical properties. The thermal stability of these contacts was also examined by annealing process. The specific contact resistance of the contacts has been measured by the transmission line method (TLM).

The results of this research show that;

At room temperature, the (I-V) characteristics for all (metal/ZnS) structures except (Au/ZnS) showed an excellent Ohmic behavior over the entire voltage range (-100 to 100 V), however (Au/ZnS) structures exhibited Ohmic trend only in the low voltage range.

The In electrode is available as an Ohmic contact on the n-type ZnS films, and its obtained specific contact resistance to be of an order of magnitude lower than that of other metals. The annealing process resulted in the lowest specific contact. The obtained specific contact resistances can be accurate through the change in the geometric design of the mask used for the electrode construction by increasing the contacts width and decreasing the contacts space separation.

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