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Accurate Estimation of Low ($< 10^{-8} \Omega \cdot \text{cm}^2$) Values of Specific Contact Resistivity

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Abstract—Advancements in nanotechnology have created the need for efficient means of communication of electrical signals to nanostructures, which can be addressed using low resistance contacts. In order to study and estimate the resistance of such contacts or the resistance posed by the interface(s) in such contacts, accurate test structures and evaluation techniques need to be used. The resistance posed by an interface is quantified using its specific contact resistivity (SCR), and although multiple techniques have been utilized, inaccuracies of such techniques in measuring values of SCR lesser than $10^{-8} \Omega \cdot \text{cm}^2$ have been reported. In this letter, an approach for estimating very low values of SCR (lower than the previously limiting $10^{-8} \Omega \cdot \text{cm}^2$) using a cross Kelvin resistor test structure is demonstrated using aluminum to titanium silicide ohmic contacts, with a minimum estimated SCR value of $6.0 \times 10^{-10} \Omega \cdot \text{cm}^2$.

Index Terms—Contact resistance, cross Kelvin resistor (CKR), specific contact resistivity (SCR).

I. INTRODUCTION

ADVANCEMENTS in nanotechnology have created the need for efficient means of communication of electrical signals to nanostructures [1]. Electrical contacts made to such nanodevices need to pose minimum possible contact resistance. In order to study and estimate the resistance of such contacts or the resistance posed by the interface(s) in such contacts, accurate test structures and evaluation techniques need to be used. These will pave the way to the identification of new materials and/or contact architectures to develop nanoscale low resistance contacts.

The resistance posed by an interface is quantified using its specific contact resistivity (SCR), which is denoted using ρ_c (in ohm square centimeters) [2], and multiple techniques have been utilized in measuring SCR values. Cross Kelvin resistor (CKR) test structures were shown to be suitable for the measurement of low values of SCR, but the use of cumbersome error correction curves to estimate the value of SCR and inherent inaccuracies in the technique served as deterrents from the widespread use of this estimation technique [3]–[6]. Using a combination of analytical calculations and finite element modeling, a simplified approach to this problem of SCR estimation using the CKR test structures with varying contact sizes has been developed by the authors of this letter [7]. This letter demonstrates the accuracy

Fig. 1. Schematic of a CKR test structure. Notations used in the manuscript are denoted.

of this technique in estimating SCR lower than the previously limiting values of 10^{-8} to $10^{-7} \Omega \cdot \text{cm}^2$.

The accurate evaluation of low values of SCR (related to low values of contact resistance) will be demonstrated using two-layer ohmic contacts with aluminum and titanium silicide thin films. Although these ohmic contacts have been characterized before [8], they remain one of the very few ohmic contacts for which very low ($< 10^{-8} \Omega \cdot \text{cm}^2$) values of SCR have been reported.

II. CKR TEST STRUCTURE

The CKR test structure [9]–[11], as shown in Fig. 1, consists of two “L”-shaped regions (of width w), consisting of the two materials of interest, which, in this case, are aluminum (upper “L”) and titanium silicide (lower “L”). For contact resistance estimation, the CKR test structures using contacts of defined areas (circular or square contacts with diameter or side d , respectively) are used; achieved by defining the contact in an intermediate insulator layer, as shown in Fig. 1.

The value of resistance measured from the two voltage taps of the CKR is the Kelvin resistance R_K , which is a combination of the contact resistance R_c and other parasitic resistances (due to sheet resistance of surrounding material). R_c is inversely proportional to the area from the standard resistance–area relationship. This implies that as the area decreases, by decreasing the diameter d , R_c increases, and beyond

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Fig. 2. Comparison of the measured SCR values before, after 30 min, and after 300 min of annealing at 450 °C for the CKR test structures with silicide arm width of 9 μm . The curves drawn for each set of data points are representative and are only to assist the reader in extrapolation of the data.

a point will dominate the parasitic effects. An infinitesimally small contact will exhibit maximum R_c , and the R_K measured will be the closest to the actual R_c value. Hence, by obtaining a number of resistance values, which include parasitic errors, the true SCR value (ρ_c , which is different from the measured SCR ρ'_c) can be estimated by extrapolating to an ideal point contact.

III. EXPERIMENTAL DETAILS

Silicon samples coated with 100-nm titanium were patterned (using photolithography) to form the titanium silicide (TiSi_2) arms of the CKR test structures. Formation conditions of C54 titanium silicide are described in [12]. After the formation of TiSi_2 , 100 nm of silicon dioxide (SiO_2) was deposited on the samples and patterned by etching in a buffered hydrofluoric acid solution to form circular contacts of a variety of diameters. A 600-nm aluminum (Al) layer, which was deposited by electron beam evaporation, was patterned to form the upper arms of the CKR test structures.

These steps defined the CKR structures of varying contact sizes d and three different CKR arm widths w . These Al– TiSi_2 contacts were annealed, in an atmosphere of 3% hydrogen in nitrogen, at 450 °C or 500 °C in steps of 30 min, to convert them from Schottky to ohmic contacts. The SCR measurements were carried out using a micromanipulator probe station after each annealing step in order to study their variations with annealing time (up to 300 min) and temperature (450 °C or 500 °C). Annealing was not carried out at temperatures beyond 500 °C due to the diffusion of aluminum into silicon through the titanium silicide thin film [13], [14].

IV. RESULTS AND DISCUSSION

The SCR measurements were interpreted using the technique described in [7]. The graphs shown in Fig. 2 indicate the measured SCR values ρ'_c for Al– TiSi_2 ohmic contacts annealed at 450 °C; these measured values include parasitic resistance

TABLE I
MEASURED AND ESTIMATED VALUES OF SCR FOR Al– TiSi_2 OHMIC CONTACTS ANNEALED AT 450 °C FOR DIFFERENT ANNEALING DURATIONS (CKR ARM WIDTH OF 9 μm)

Anneal time (minutes)	$\rho'_c(\text{max})$ (Ωcm^2)	$\rho'_c(\text{min})$ (Ωcm^2)	ρ_c (Ωcm^2)
0	1.7×10^{-5}	9.1×10^{-7}	$2.0 \pm 0.5 \times 10^{-7}$
30	8.3×10^{-8}	1.7×10^{-8}	$6.0 \pm 1.0 \times 10^{-9}$
60	6.8×10^{-8}	1.6×10^{-8}	$6.0 \pm 1.0 \times 10^{-9}$
90	6.4×10^{-8}	1.5×10^{-8}	$5.0 \pm 1.0 \times 10^{-9}$
120	6.2×10^{-8}	1.5×10^{-8}	$4.5 \pm 1.0 \times 10^{-9}$
180	5.6×10^{-8}	1.2×10^{-8}	$4.0 \pm 1.0 \times 10^{-9}$
240	5.4×10^{-8}	9.0×10^{-9}	$3.0 \pm 0.5 \times 10^{-9}$
300	5.2×10^{-8}	8.6×10^{-9}	$2.0 \pm 0.5 \times 10^{-9}$

TABLE II
MEASURED AND ESTIMATED VALUES OF SCR FOR Al– TiSi_2 OHMIC CONTACTS ANNEALED AT 500 °C FOR DIFFERENT ANNEALING DURATIONS (CKR ARM WIDTH OF 9 μm)

Anneal time (minutes)	$\rho'_c(\text{max})$ (Ωcm^2)	$\rho'_c(\text{min})$ (Ωcm^2)	ρ_c (Ωcm^2)
0	1.5×10^{-5}	9.0×10^{-7}	$4.0 \pm 1.0 \times 10^{-7}$
30	2.5×10^{-8}	6.0×10^{-9}	$3.0 \pm 0.5 \times 10^{-9}$
60	2.3×10^{-8}	4.0×10^{-9}	$2.0 \pm 0.5 \times 10^{-9}$
90	2.2×10^{-8}	3.3×10^{-9}	$1.5 \pm 0.5 \times 10^{-9}$
120	1.8×10^{-8}	3.0×10^{-9}	$1.0 \pm 0.5 \times 10^{-9}$
150	1.6×10^{-8}	2.4×10^{-9}	$9.0 \pm 2.0 \times 10^{-10}$
180	2.2×10^{-8}	2.0×10^{-9}	$6.0 \pm 1.0 \times 10^{-10}$

contribution, and the true SCR value ρ_c is extracted from a collection of these values. Fig. 2 shows the measured SCR values for the CKR structures with varying contact diameters and arm width of 9 μm . The graph clearly indicates the steep fall in the SCR values on annealing the contacts for 30 min. Subsequent annealing further reduces the values. Table I summarizes the results obtained. The lowest measured ρ'_c value ($8.6 \times 10^{-9} \Omega \cdot \text{cm}^2$) can be extrapolated to yield a true SCR value of $2.0 \times 10^{-9} \Omega \cdot \text{cm}^2$.

Similar measurements were also carried out by annealing at 500 °C, and the results are summarized in Table II. It can be observed that the increased annealing temperature promotes faster decrease in the measured SCR values. Fig. 3 illustrates the SCR values measured after 180 min of annealing for the different CKR linewidths. The measured SCR values are higher for widths of 21 and 32 μm due to larger parasitic resistances contributed by the silicide sheet resistance, which increases as w increases [7]. The lowest measured ρ'_c value ($2.0 \times 10^{-9} \Omega \cdot \text{cm}^2$) can be extrapolated to yield an SCR value

Fig. 3. Comparison of the measured SCR values after 180 min of annealing at 500 °C for the CKR test structures with silicide arm widths of 11, 21, and 32 μm . The curves drawn for each set of data points are representative and are only to assist the reader in extrapolation of the data.

of $6.0 \times 10^{-10} \Omega \cdot \text{cm}^2$. Further annealing beyond 180 min did not reduce the SCR values. This SCR value of $6.0 \times 10^{-10} \Omega \cdot \text{cm}^2$ is the lowest reported for any two-layer contact.

The error in the measured SCR values is very small, which can be observed from the limited scatter in the data presented. The true SCR values estimated from the measured set of values has an error of about 25%, which is highly acceptable, considering the range of the SCR values under consideration (10^{-10} to $10^{-8} \Omega \cdot \text{cm}^2$). These experimental results were also verified using finite element modeling.

V. CONCLUSION

The results discussed in this letter highlight the ability of the proposed technique, using the CKR test structures, in accurately estimating very low values of SCR, with the lowest estimated value of $6.0 \times 10^{-10} \Omega \cdot \text{cm}^2$ for the aluminum to titanium

silicide contacts. The use of this simplified approach will be beneficial in evaluating submicrometer contact structures [15] and developing electrical contacts to nanodevices.

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