A Study of The Hole Barrier of Kanthal on Silicon Using Current – Voltage Characteristics

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DOI: https://doi.org/10.51584/IJRIAS.2023.8406

Received: 28 October 2022; Accepted: 17 November 2022; Published: 28 April 2023

Abstract : - We report fabrication of a kanthal pSi diode and a study of its hole barrier by Current – Voltage characteristics. The diode fabrication was done by sputter-depositing a kanthal film on a single crystalline p – type Si in the <111> orientation. Kanthal is a metal alloy consisting of 70.6% Iron, 24.1% Chromium, 4.8% Aluminum and 0. 5% Co. The hole barrier on kanthal was determined by I – V characteristics to be Φ_{Bh}=0.66±0.03 eV. The Rutherford Back Scattering Analysis shows that the composition of the sputtered kanthal films and the parent target are the same.

Key Words: Kanthal, p – type silicon, Barrier height, Sputtering, Thin Solid Films, Diodes, Rectifier, Ohmic.

I. Introduction

Metal-semiconductor interfaces are of crucial importance in all types of solid state devices. In this paper we report a study on a metal –semiconductor in which kanthal was deposited by sputtering technique on p-silicon.

In this study Kanthal was deposited by rf sputtering a kanthal target on p – Si. Kanthal is a metal alloy consisting of 70.6% Iron, 24.1% Chromium, 4.8% Aluminum and 0.5% Cobalt. The sputtered kanthal films on Si are very stable and do not corrode, even though the major parent element Iron is highly corrosive as they can produce durable and stable devices.

The barrier height of kanthal films can be very useful for solid state devices, hybrid and integrated electronics.

In view of these possible applications, the hole barrier of Kanthal on Si was studied. The barrier height is an important property of a diode since it determines whether the diode will be a rectifier or ohmic.

After fabrication of the diodes, the barrier was determined using both the forward and reverse I – V characteristics. The method of I-V characteristics is described in the next section.

II. Materials and Methods

2.1 Barrier Height Determination

There are two methods which can be used to measure the barrier height of a diode using I-V characteristics. These are: the forward I-V characteristics and the reverse I-V characteristics [Sze 1981].

The forward I-V characteristics are obtained for a metal-semiconductor (MS) interface when the metal is negatively biased. The current equation is then given by:

$$I = A^{**}AT^2 \exp\left(-\frac{q\Phi_{Bh}}{kT}\right)\left[\exp\left(\frac{qV}{kT}-1\right)\right] \quad (1)$$

Where I = forward current through the junction

A** = Richardson's constant for holes

A = Area of the MS junction (or diode)

Φ_{Bh} = Hole barrier height of the Si diode

q = Electronic charge.

T = Absolute temperature in Kelvin

k = Boltzmann constant

V = Forward bias on the diode.

From equation (1) the current density through the diode is given by:

$$J = A^{**}T^2 \exp\left(-\frac{q\Phi_{Bh}}{kT}\right)\left[\exp\left(\frac{qV}{kT}-1\right)\right] = J_0\left[\exp\left(\frac{qV}{kT}-1\right)\right] \quad (2)$$

Where:

$$J_0 = A^{**}T^2 \exp\left(-\frac{q\Phi_{Bh}}{kT}\right) \quad (3)$$

If $V >> \frac{kT}{q}$, then $J \approx J_0 \exp\left(\frac{qV}{kT}\right)$ and hence: $\ln\left(\frac{J}{J_0}\right) = \frac{qV}{kT}$

Using this information in (2) and rearranging terms we get:

$$\ln\left(\frac{J}{T^2}\right) = \ln A^{**} - \frac{q}{kT}\left(\Phi_{Bh} - V\right) \quad (4)$$

Thus a plot of $\ln\left(\frac{J}{T^2}\right)$ versus $\frac{1}{T}$ at fixed values of V, is a straight line with gradient:

$E_A = -\frac{q}{k}\left(\Phi_{Bh} - V\right)$ from which :

$$\Phi_{Bh} = -\frac{E_A}{q}k + V \quad (5)$$

can be calculated for each value of V.

If we change the polarity of the voltage in equation (2), by reversing the direction of the current, we obtain the equation for reverse I-V characteristics given by:

$$J = J_0\left[\exp\left(-\frac{qV}{kT}\right) - 1\right] \quad (6)$$

Again if $V >> \frac{kT}{q}$, we have $J \approx -J_0$,

$$\ln\left(\frac{J_0}{T^2}\right) = \ln A^{**} - \frac{q\Phi_{Bh}}{kT} \quad (7)$$

Plotting $\ln\left(\frac{J_0}{T^2}\right)$ versus $\frac{1}{T}$, we obtain a straight line with gradient g from which the barrier height:

$$\Phi_{Bh} = -\frac{gk}{q} \quad (8)$$

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS | Volume VIII Issue IV April 2023

can be calculated.

2.2 Diodes Fabrication

The fabrication of the diodes was done by RF-sputtering a kanthal target and depositing a thin kanthal film on a p-Silicon substrate in the <111> orientation. Initially the silicon wafers were cleaned, polished and etched following a standard procedure [Watanabe etal 2005 and Ringwood etal 2010].

The chemically cleaned wafers of resistivity 500 Ω-cm were mounted in the sputtering chamber. Pre-sputtering of the Kanthal target was done while the wafers were shielded. This was meant to clean the target. Sputter-deposition of the kanthal films was done (with the shields removed) at a sputtering power of 400 watts for 3-10 minute at a rate of 120 Å per minute. Sputtering was done with Argon gas at a pressure of $5x10^{-3}$ Torr. After the first deposition, half of the wafers were turned upside down to obtain back to back contacts with kanthal films. The remaining wafers were deposited with kanthal films on only one side of the wafers. After deposition, the areas of the sputtered kanthal on the devices was found to be between 0.127 cm^2 and 0.636 cm^2. The thickness of the kanthal films varied from 400 Å to 1500 Å.

After this the wafers were taken outside the sputtering chamber for characterization. The Current – Voltage characteristics method described in section 2.3 was used to determine the barrier height.

2.3 Current – Voltage Measurements

The diodes were mounted one after another in a cryostat in which the temperature was lowered below room temperature using liquid nitrogen. I-V characteristics at room temperature (296 K) and activation plots were measured. Initially both forward and reverse I-V characteristics were taken at room temperature. Then activation plots were made only for the reverse characteristics. The temperature in both cases was measured with the help of a thermo-couple system where the reference junction was maintained at 0 ^oC by keeping it in ice in equilibrium with water.

2.4 Rutherford Back Scattering Analysis

The composition of the deposited kanthal films was studied by Rutherford Backscattering (RBS) Analysis, [Vu Duc Phu etal.2016] using ${}^{16}O_8$ ions with incident kinetic energy of 20 MeV. The kanthal films used in the RBS analysis were fabricated simultaneously with the diodes. The multichannel analyzer had a calibration of 30.0 keV/channel. With five detectors mounted in a circle, a total resolution of 150 keV/channel could be realized.

The results of all the measurements, including the RBS analysis are summarized in the next section.

III. Results

3.1 Barrier Height Determination

A graph of I versus V was plotted for reverse an I-V forward bias for the diodes. Then $\log\left(\frac{I}{BAT^2}\right)$ versus $\frac{1}{T}$ plots at different bias voltages were investigated by straight line fitting. Where $I = JA$ is the current, A the area of the diode and B is a correction due to the image force lowering. B is given by $B = \exp\left(\frac{q\sqrt{q\,F/4\pi\varepsilon_s}}{kT}\right)$. In this equation ε_s is the dielectric constant of the silicon. F is the electric field resulting from biasing the diode. From such plots, the barrier height of the diode was obtained as described earlier.

The results of a reverse biased Kanthal – pSi – Kanthal junction at different temperatures are shown in figure 1(a).

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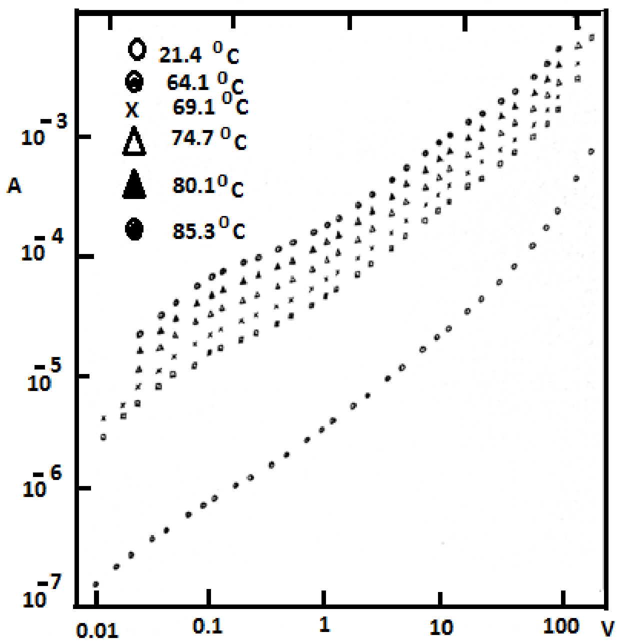

Figure 1(a): Reverse biased Kanthal – pSi – Kanthal at different temperatures

The activation energy for this data, deduced from the low voltage s 0.1 V, 0.2V and 0.4V was approximately constant. The average value of the barrier height obtained in this way was Φ_{Bh} = 0.68 eV. The activation plot for this data, obtained by using equation (7), are shown in figure 1 (b).

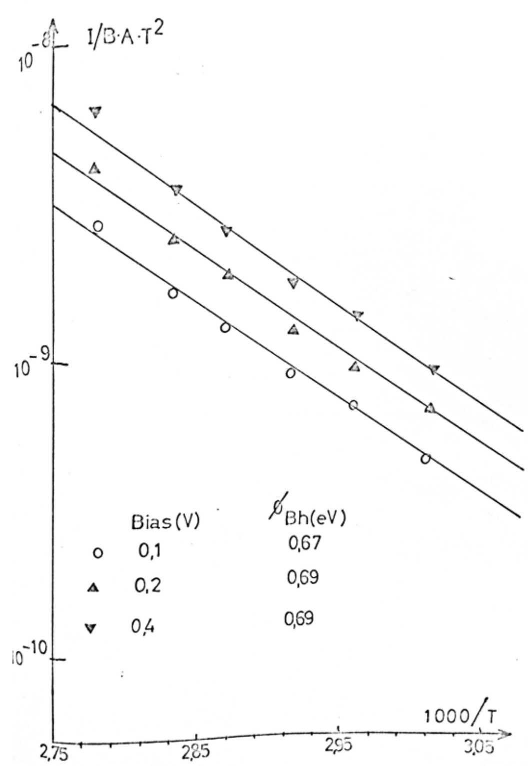

Figure 1(b): Activation Plots of the Data in Figure 1(a)

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In figure (2) is shown the forward I-V data. Here the Kanthal-pSi junction was forward biased by putting a negative voltage on the kanthal contact.

A least squares fit was made to the points in the region 0.08 V and 0.18 V of the I-V characteristics. This gave a saturation current of 5×10^{-6} Amps. From the known area of 0.2 cm^2 for the diode and assuming a value for the Richardson constant for holes of 30 $AK^{-2}cm^{-2}$, we derive a value of $\Phi_{Bh} = 0.66$ eV.

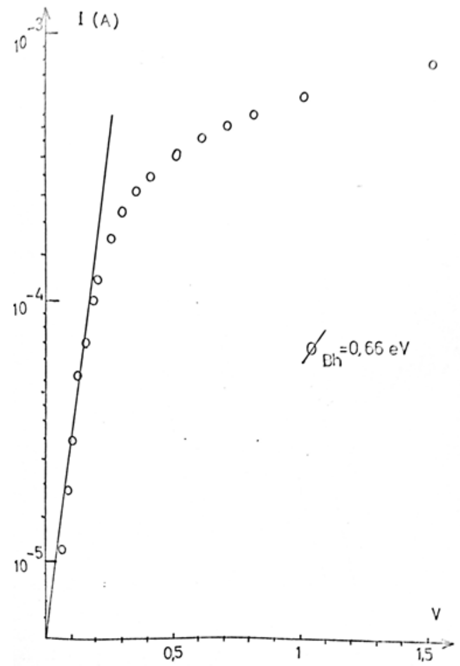

Figure 2: Forward Characteristics for Kh$^-$ - pSi – In(Hg) Structure

The I-V data for a Kanthal – pSi – Kanthal diode in one direction are shown in figure 3(a).

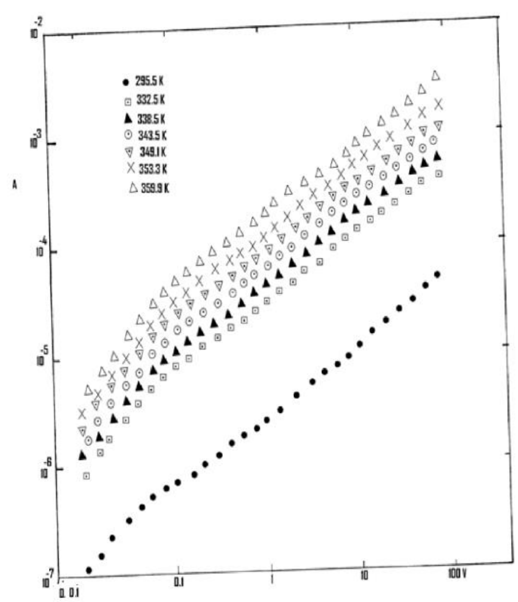

Figure 3(a): I-V data for a Kanthal – pSi – Kanthal diode in one direction

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS | Volume VIII Issue IV April 2023

This diode was fabricated using 400 W sputter power for 7 minutes.

The activation plots of these data are shown in Figure 3(b). From these results, activation energy of 0.67 to 0.69 eV was calculated over the voltage range 1.0 to 2.0 V (See figure 3(b)).

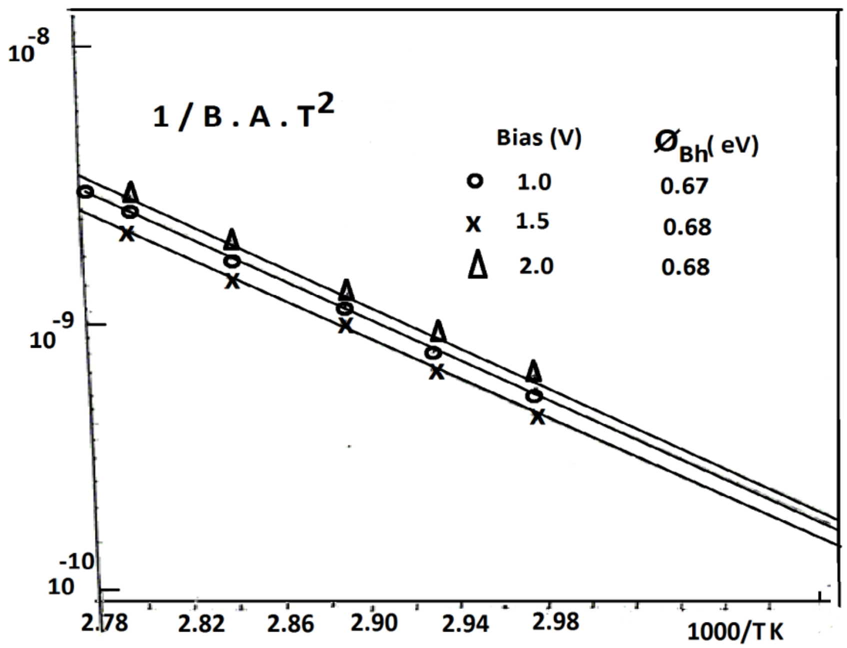

Figure 3(b): Activation plots for the data in Figure 3(a)

3.2 RBS Analysis Results

The Kanthal films used in the analysis were deposited on a Ge-Al_2O_3 substrate. Figure 4 shows a typical RBS analysis spectrum obtained in this study.

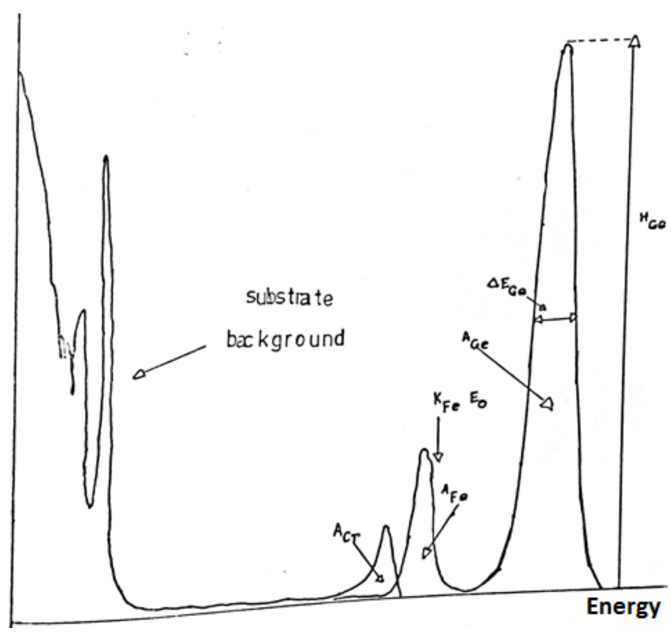

Figure 4: Typical RBS analysis spectrum obtained in this study

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS | Volume VIII Issue IV April 2023

IV. Discussion

Annealing of samples tended to lower the hole barrier for all samples. These findings are in agreement with what other workers have found while working on different materials

[Monch 1990, 1994]. The results should be interpreted with a model involving the introduction of donor-like centers by sputter-damage.

In addition we wish to comment on the S-shape of the I-V characteristics (see figure 1(a)). The first trend of flattening-off of current is due to saturation when $V >> \frac{kT}{q}$, and the second may be due to space-charge limitation effects as discussed by [Rhoderick and Williams 1988] and by [Sze 1981].

The composition of the Kanthal films is approximately the same as the parent material, as revealed by the RBS analysis. The composition of the Kanthal target was given by the manufacturer [Bulten-Kanthal AB 2016] as: 70.6% Fe, 24.1% Cr, 4.8% Al and 0.5% Co. ratios by volume. This means that the proportion by volume of Chromium to Iron is $V_{Cr}/V_{Fe} = 0.341$ in the target. From the RBS analysis (figure 4) we find this ratio to be 0.34 ± 0.02 in the films which is nearly the same as in the parent material.

V. Conclusions

A diode was fabricated successfully using kanthal films on pSi for the first time. The hole barrier height of the diode was measured and found to be $\Phi_{Bh} = 0.67 \pm 0.03$eV

The RBS analysis confirmed that the composition of the fabricated kanthal films and that of the parent material were the same.

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