

A novel evaluating method to determine fractal dimension of SEM images: a study of heat treated Au/Pd/GaAs contacts

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The heat treatment is an essential step of making Ohmic contacts to compound semiconductors. During the heat treatment a remarkable volatile component (arsenic) loss takes place due to the thermal decomposition of GaAs and the interactions between Ga and the contact metals. Using scanning electron microscope combined with mass spectrometer (constructed at our institute) it was possible to perform 'in situ' studies on the contacts. We examined the changes of the surface pattern and measuring the arsenic evaporation during heating up the sample to 630 °C. The volatile component loss vs. temperature (EGA) curve shows two peaks before the rapid decomposition of GaAs substrate begins at around 600 °C. Examining the 'in situ' SEM images of the surface we proved, that from the first evaporating peak the contact structure can be described by its fractal characteristics. The SEM pictures show homogenous shape below 375 °C; above this temperature separate clusters emerged. We found between 375 °C and 400 °C and above 620 °C two, and between 420 °C and 600 °C three different clusters in the images, respectively. We introduced a new method (soft segmentation) to determine the fractal dimension (D) of multi-cluster images. The soft segmentation can be used for any number of clusters, and it is applicable to determine the 'joint fractal dimension' of any clusters treated as one.

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1. Introduction

The heat treatment is an important step of semiconductor technology. During the heat treatment the contacts obtain their desired characteristics: the type of the contact changes from Schottky to Ohmic, contact resistivity and some mechanical properties (such as bonding ability and adhesion to the substrate) changes as well [1].

During the heat treatment of contacts to A^{III}B^V type compound semiconductors the A^{III} component interacts with the contact metal(s) while the B^V component evaporates. Before the rapid thermal decomposition of the substrate at higher temperatures, peak(s) can be observed due to these interactions in the EGA curve. The characteristic temperature(s) of the evaporation peak(s) is (are) determined by the thickness of the contact metal(s) and the number of the metallization layers [2].

In our laboratory we constructed a scanning electron microscope combined with quadrupole mass spectrometer, which makes it possible to record the volatile component loss vs. temperature curve and to take 'in situ' SEM images of the surface during the heat treatment [3].

In our earlier studies we found fractal properties of 'in situ' SEM images of A^{III}B^V semiconductor contacts. We also proved that there is a correlation between the fractal behavior of the surface pattern and the characteristic temperatures of the EGA curve [4,5].

This surface pattern formation caused by interdiffusion and surface reaction during the heat treatment [6]. Some details of the reactions were published in Ref [7].

In the present paper we examined the fractal character of the surface morphology of (85 nm) Au/ (50 nm) Pd / GaAs (100) contacts and found correlation between the fractal properties of the SEM images and the EGA curve. We developed a new method (soft segmentation) to analyze the fractal properties of SEM images. The soft segmentation method is applicable to analyze images having not only two, but also three or more clusters in it. In the present paper we demonstrate the application of this procedure on a two-layer gold/palladium metallization on GaAs, which had fractal properties of the surface with two or three separate clusters on it depending on the temperature during the heat treatment.

2. Experimental details

The surface morphology of the (85 nm) Au/ (50 nm) Pd metallization deposited on (100) GaAs single crystal doped by Sn with the carrier concentration of $2 \times 10^{23} \text{ m}^{-3}$.

In spite a new proposal (eg. cooling [8]) during the deposition the substrate was preheated up to 200 °C.

The samples after the deposition were examined during heat treatment in a scanning electron microscope

(JEOL JSM-T20) combined with a quadrupole mass spectrometer. After preparation (polishing and etching) and the deposition of the metal layers in a vacuum evaporator at a pressure lower than 10^{-4} Pa, the samples were heat treated in the mass spectrometer vacuum (at 10^3 Pa) with a heating rate of $30^\circ\text{C}/\text{min}$. During the heat treatment when the volatile component loss intensity started to grow remarkably (i.e. it was much more significant than the background noise of the mass spectrometer) SEM-BEI (Backscattered Electron Image) photographs were taken of the surface morphology. The photographs were scanned for digital processing with the resolution of 200 pixels/inch. The magnification of the SEM photographs was 500 [5].

The soft segmentation method was introduced to determine the fractal properties of the digitized greyscale SEM picture [9]. First step of the evaluation is that it must be decided, which cluster(s) is (are) to be considered as the 'fractal pattern' and which one(s) represent(s) the background. In structures having two separate clusters in their SEM pictures, one cluster is the fractal 'pattern', and the other the 'background', respectively. In the evaluation method the most characteristic shade of grey must be selected from the 0-255 range of the 256 greyscale bitmap image to be considered as the 'center' of the given cluster. After selecting these values, a function – 'grade of membership' (GM)

$$G_i(x) = \frac{1}{\sum_{j=1}^n \left(\frac{(x-v_i)^2}{(x-v_j)^2} \right)^{\frac{1}{m-1}}} \quad (1)$$

[10] is used for weighing the whole intensity domain and to separate each cluster from the other(s):

Where n is the number of clusters in the image, x is the intensity of the given pixel ($0 \leq x \leq 255$), v_i is the most characteristic shade of grey value of the examined cluster (pattern) and m is the weighing coefficient (in our case $m=2$).

The center of the clusters can be obtained with a special software written for this goal. This program displays the 256 greyscale bitmap image on the screen. Clicking on a desired pixel with the mouse the program gives back the user the intensity of the chosen pixel.

The GM function orders a value to each pixel from 0 to 1, depending how far its intensity is from the intensity of the center of the studied cluster. The value of this function is 1 when $x=v_i$ (the center of the fractal pattern), and 0 when $x=v_j \neq v_i$ (the center of the other clusters), and $1/n$ when $x \rightarrow \pm\infty$ (see Fig. 1). Where $G(x) > 0.5$, the cluster can be separated from its neighbor clearly. The m exponent is the weighing exponent, which affects the slope of the GM function. By increase of m the shape of the function gets 'sharper'. The GM function behaves like a probability-like function – which shows the grade of how much a given pixel belongs to a given cluster –, the following equation stands:

$$\sum_{j=1}^n G_j(x) \equiv 1 \quad (2)$$

By the means of this function the entire interval from 0 to 255 can be divided between the clusters that form the whole image.

The fractal dimension of the surface pattern was determined by correlation analysis, by weighing the pixels using the GM function, i.e. to each pixel a certain value between 0 and 1 were associated determined by the GM function. The density of the pattern chosen by the user in a place is the GM function value of the greyscale of the pixel:

$$\rho(r) = G_i(x(r)), \quad (3)$$

where r is the place coordinate of the pixel and $x(r)$ is the image itself (see Fig. 2).

Where the shape of the $\ln\text{-}\ln$ plot of the average pixel number (M) of the pattern versus linear box size (L) is straight, it indicates that the analyzed sample is a real fractal. In this case the slope of the plot gives the fractal dimension.

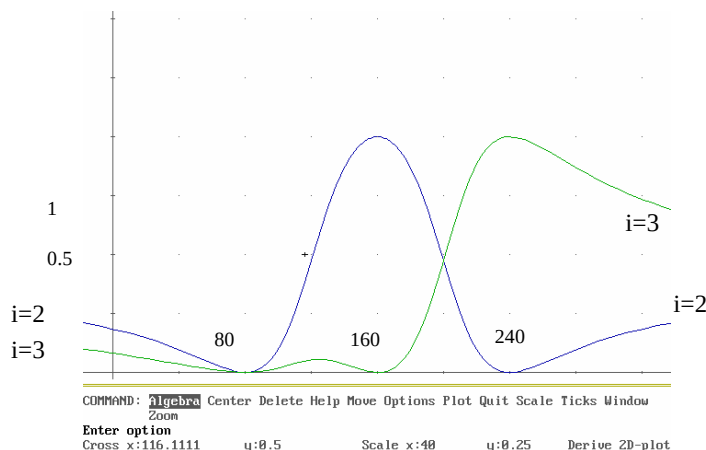


Fig. 1. The grade of membership function - an example. $n=3$, $m=2$, $v_1=80$, $v_2=160$, $v_3=240$.

In one temperature range we found two, and in other range three clusters in the SEM images of the surface. In case of the two-cluster image the 'white' pattern were the 'fractal pattern' and the 'black' one the background, because the white phase formed islands in the darker background. For the same reason in the case of the three-cluster images the white and the grey clusters were considered as fractal patterns and the black one as background.

We investigated not only the fractal dimension of the white and the grey cluster separately, but also their 'joint fractal dimension' was determined. The 'joint fractal dimension' of two clusters can be obtained by subtracting the GM function of the background cluster from 1.

In this case we considered both the white and the grey clusters to form one joint fractal pattern while the black cluster is the background.

3. Results and discussion

Heating up the (85 nm) Au / (50 nm) Pd / GaAs (100) sample, the surface pattern was homogeneous up until 375 °C. At 375 °C angular shapes appeared in the images. At higher temperatures these shapes grew bigger, resulting in a complex structure. Over 375 °C up to the peak temperature of the heat treatment (630 °C) firstly two (between 375 and 400 °C), then three (between 420 and 600 °C), and then two segregated phases could be observed again on the contact surface over 600 °C.

From the increasing of the first evaporating peak the surface showed fractal character up until the peak temperature of the heat treatment (Fig. 3)

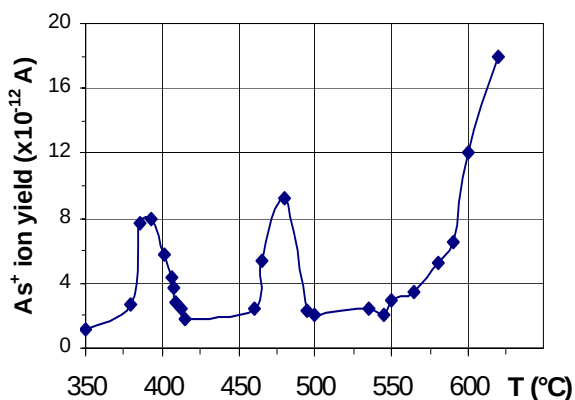


Fig. 3. The EGA curve of As evaporation of the (85 nm) Au / (50 nm) Pd / GaAs (100) sample during heat treatment.

Three clusters were found on the contact surface from the top end of the first evaporating peak of the EGA curve up until 600 °C, where the As evaporation starts to grow

rapidly due to the thermal decomposition of the GaAs substrate.

The fractal dimensions (D) determined for the 'in situ' images can be seen on Fig. 4.

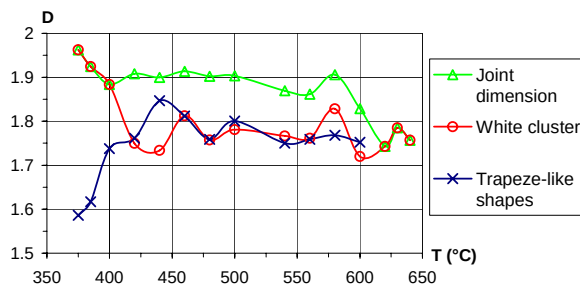


Fig. 4. The fractal dimensions corresponding to the temperature of the (85 nm) Au / (50 nm) Pd / GaAs (100) sample during heat treatment.

The green curve represents the fractal dimension of the pattern in that range, where the surface has two clusters, and the 'joint fractal dimension' of the grey and the white clusters where three clusters can be observed, respectively. Between 420 °C and 600 °C the red and the blue curves are for D of the white and the grey phases.

In general D decreases by the growth of the evaporation, while the 'joint fractal dimension' hardly changes.

It can be seen clearly, that around 360 °C trapeze-like patterns have appeared, which - according to our opinion - cause the Ohmic contact. Other authors got previously Ohmic contacts at this temperature [11]. At this temperature range we have measured As loss peak. The growing up phenomenon of the trapeze-like patterns, which is visible to the naked eye on the SEM pictures, is correlated with the maximum value of the fractal dimension. This phenomenon shows the entropy feature of the dimension, because if a set is growing, that means the dimension can't decrease. Lamouche et al. [11] measured the optimum temperature of the Ohmic contact at 500 °C, at which temperature we measured another As loss maximum value. The disappearing of the trapeze-like patterns starts above 500 °C, according to our measurements this is the temperature range where the decomposition of the compound semiconductor (GaAs) starts.

4. Conclusions

We demonstrated that the new fractal counting method (soft segmentation) has the less subjectivity.

We found correlation between the appearance of the trapeze-like patterns, the behavior of the fractal dimension, the temperature values of the As loss maximums. An agreement was also found with the measured by another authors appearance of the ohmic contact and the measured

outevaporation of volatile component from the metallized compound semiconductor material.

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