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An Introductory Investigation of the Breakdown Mechanism in Electro-Discharge Machining

by

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Summary

As an introductory investigation of the breakdown mechanism in electro-discharge machining the breakdown mechanism of pure liquids has been investigated.
Starting from a number of experiments the existing breakdown theories have been tested as to their validity.It appears that they cannot be applicated in the region of field intensities which has been used in the experiments.
A thermal model of the breakdown mechanism has been evolved.

Zusammenfassung

Als einleitende Untersuchung nach das Durchschlagmechanismus bei funkenerosiver Bearbeitung wurde das Durchschlagmechanismus in sauberen Flüssigkeiten erforscht.
Mittels einer Anzahl von Experimenten wurden die üblichen Theorien auf ihre Anwendbarkeit geprüft.Dabei stellte sich heraus,dass diese Theorien im untersuchten Bereich der Felddichten nicht zutreffen.
Im vorliegenden Beitrag wird ein thermisches Modell des Durchschlagmechanismus entwickelt.

Résumé

Pour introduction à l'enquète du mécanisme de décharge dans l'usinage par étincelles le mécanisme est étudié en liquides purs.
Basé sur un nombre des expériments les théories existantes sont contrôlées à leurs applicabilité.Elles ne se trouvaient pas applicable dans le région des intensités investigé.
Une modèle thermique du mécanisme de décharge est projetée.

1. Introduction

It is a familiar phenomenon in electro-discharge machining (EDM) that some time passes after applying the breakdown voltage across the working gap and the breakdown itself. This time is called the "ignition delay".
The research done by Kok,Zolotykh,Trofimowa and Kovács has shown,that impurities in the liquid affect the breakdown mechanism (1,2,3).However,in this investigation only a pure liquid (n-hexane) has been used,because it is hardly possible to describe exactly the breakdown mechanism of polluted liquids,if the mechanism is not known for pure liquids; the less so when considering that the breakdown strengths of pure liquids are of the same magnitudes as the field intensities applied in EDM (10^4 to 10^5V/mm).

2. Breakdown theories of pure liquids

In the past a number of investigators have tried to describe the breakdown mechanism of pure liquids in a similar way as in gases:the breakdown of liquids would be introduced by collisional ionisation of the molecules of the liquid.Existing theories are:

a. Theory of Von Hippel.Breakdown takes place when the number of collisions of electrons with the molecules of the liquid,resulting in ionisation of these molecules,exeeds the number of recombinations.Von Hippel supposes no distribution in electron energies.

b. Theory of Fröhlich.Identical to Von Hippels theory,but Fröhlich assumes an electron energy distribution.

c. Theory of Seitz.Breakdown takes place as soon as the diameter of the avalanche build-up by collisional ionisation reaches a critical value.

However,it can not be said for certain whether the mechanism of breakdown of a liquid is comparable to that of gases,because the mean free path of the electrons in a liquid is much smaller than in gases.Hence,the energy gained

by an electron during the mean free passage,in consequence of the field intensity,is also much smaller.
To ascertain whether breakdown of liquids is comparable with that of gases,consider the formula describing the electric current in a gap filled with gas,caused by collisional ionisation of the gas atoms (4):

$$i = \frac{i_e(0)e^{\alpha s}}{1-\gamma(e^{\alpha s}-1)} \qquad (1)$$

where $i_e(0)$ is the primary electron current at the cathode (caused by photo,thermal or field emission),s the gap width, α the ionisation coefficient of Townsend presenting the number of ionising collisions of an electron with gas atoms when the electron covers one mm in the direction of the field,γ the secondary emission coefficient defined as the number of electrons emitted secondarily at the cathode per primary electron arisen in the gap from collisional ionisation.The emission of secondary electrons is caused by collision of ions and metastable atoms on the cathode and by radiation energy emanating from excited atoms.
According to the criterion of Townsend breakdown takes place when the current becomes very large,i.e. if:

$$1-\gamma(e^{\alpha s}-1) \approx 1-\gamma e^{\alpha s} = 0 \qquad (2)$$

For α and γ the following relations hold:

$$\frac{\alpha}{p} = f(\frac{E}{p}) \qquad \gamma = g(\frac{E}{p}) \qquad (3)$$

where p is the gas pressure and E the field intensity.
If the breakdown of a liquid is a result of an ionisation process of the molecules of the liquid,similar relations as in gases should exist for liquids.To investigate whether the breakdown is caused by an ionisation process,the following experiments can be carried out.

1.Determine the influence of the pressure on the breakdown mechanism.The influence of the pressure in a gaseous discharge can be explained by the reduction of the mean free path of the electrons.As a liquid is taken to be an incompressible medium, no influence of the pressure on the breakdown mechanism would be expected.
2.Determine the influence of the gap width on the current at constant pressure and constant intensity (in this case α and γ are constants).If the breakdown is caused by ionisation of the molecules of the liquid,then,as it appears from equation 1,the current is strongly dependent on the gap width.

3. Equipment

To obtain the conditions at which breakdown of a dielectric liquid takes place,it would be necessary to create field intensities of about 10^4 to 10^5 V/mm in a 5 to 40 μm gap.
In order to adjust the gap width with sufficient accuracy,electrode distances ranging from 80 to 800 μm are used.The voltage across the gap is increased in order to obtain field intensities as mentioned above.
For the experiments the pulse generator reproduced in fig.1 has been developed.
The pulse generator G produces a rectangular voltage pulse of magnitude 10V.After amplification this pulse is supplied to the control grid of tube B_1,which in its turn will conduct.Now capacitor C_2 will discharge and the then formed voltage pulse of amplitude U_2(2.5kV) is supplied to the ignition electrode of a high voltage air gap-switch S,which can handle high voltages up to 20kV(switching time 10^{-9}s).
When a discharge in the switch takes place,capacitor C_1 will be able to discharge and the potential difference U_1(3 to 20kV) will be supplied to the working gap P.
Because the time constant R_2C_1 is chosen very large with respect to the duration of the excited pulse the pulse will be almost rectangular.

4. Experiments

The figures 2 to 9 show the experimental results.
Fig.2 illustrates the influence of the pressure on the ignition delay for E = $9.5.10^4$ V/mm and 60Ru(μ inch CLA) roughness of the electrodes(copper to copper).Sandblasting is applied to obtain a roughness profile which is comparable to that obtained in EDM.
Figs. 3,4,5,6 show the current density (J) in the gap before breakdown as a function of the intensity for roughnesses 5,75, 125 and 200Ru,respectively(cathode:copper,anode:steel).
From these figs. are derived figs. 7,8,9,which show the current density at constant intensity and atmospheric pressure as a function of the gap width(s),with the roughness of the electrode surfaces as parameter(cathode:copper,anode:steel).

5. Conclusions

If breakdown of a liquid is caused by collisional ionisation of the molecules of the liquid,it would not be expected that the pressure influences the breakdown mechanism.However,fig. 2 shows that the pressure exerts great influence.
From figs.7,8,9 it appears that the current density (and also the current) is not dependent on the gap width at constant pressure and constant intensity.
From figs.2,7,8,9 it can be concluded that the breakdown of a liquid (at least for values of E which have been used) is not caused by collisional ionisation of the molecules of the liquid.
In what other way may the current in the gap be explained?
By investigation whether the measured currents,figs.3,4,5,6,obey the field emission equation of Nordheim and Fowler:

$$i = 6.2\cdot10^{-8}\frac{\sqrt{\mu}}{(\mu+\theta)\sqrt{\theta}}E^2Se^{-\frac{6.8\cdot10^6\theta^{3/2}}{E}} \qquad (4)$$

where i is the current(A),S the emitting surface(mm^2), μ the Fermi level(eV), θ the work function of the cathode(eV).
If the current can be explained by eq.4,then a plot of $\ln(i/E^2)$

versus 1/E should give a straight line.As fig.10 shows this is true,indeed.However,the value of θ calculated with this plot is much smaller than the familiar value of approx.4.5eV. The low value can be explained by the roughness of the electrode surface.It is known that the roughness of the surface decreases θ ,caused by an increase in intensity at the surface. In literature a correction factor "m" on the intensity is introduced.However,there is some ambuigity about the value of m.With m = 200, θ becomes 1.45eV.
Moreover,the oxide layer which is present on the electrode surface must be taken into account and this also decreases θ. The values of the emitting surface belonging to m = 200 reach 1.3,3.0,5.8 and $16.5 \cdot 10^{-11} mm^2$ for roughnesses 5,75,125 and 200Ru,respectively.From these very small values of S(the real electrode surface is $80 mm^2$) it can be concluded that only the peaks on the surface will emit.
In figs.3,4,5,6 the points are marked in which breakdown occured.Considering the magnitude of power per unit volume which in these points is added to the gap,it appears that this magnitude is approximately the same for all roughnesses; the mean value is $8.5 \cdot 10^{-3} J/mm^3 s$.Considering the small variations in the ignition delay in these points(the mean ignition delay was 5.3μs),it is evident that the breakdown has taken place at the same magnitudes of energy per unit volume added to the gap.

6. Thermal model of breakdown

This fact and the dependence of ignition delay on the pressure suggested a local heating of the liquid,resulting in a vapour bubble in that liquid as an introduction to the breakdown.The influence of the pressure in this case can be explained by an increase in the boiling point.Once a vapour bubble has been formed,a gas discharge may easily occur in it,causing the bubble to expand rapidly and the breakdown to spread across the whole of the gap.

It has been seen (section 5) that the current in the gap is not devided homogeneously,but in many channels (as many as there are emitting peaks).For one channel the temperature distribution as a result of the production of heat by the current in that channel can be calculated.Assume the channel is cylindrical.
See fig.11.Consider an instantaneous point source of heat at (r,φ,z) which produces a quantity of heat $qrdrd\varphi dzd\tau$ at time $t=\tau$. The temperature in the origin O resulting from this source is given by (5):

$$d(T-T_o) = \frac{qrdrd\varphi dzd\tau}{8\rho c\{\pi a(t-\tau)\}^{3/2}} e^{-(r^2+z^2)/4a(t-\tau)} \qquad (5)$$

where T_o=initial temperature(^oC),ρ= specific mass(kg/mm^3),c= specific heat(J/kg^oC),a=diffusivity(mm^2/s),q=production of heat (J/s).
By integration into the region $0\leq\tau\leq t, 0\leq r\leq R, 0\leq\varphi\leq 2\pi, -\infty\leq z\leq\infty$ the following equation can be derived which gives the temperature on the axis of a contineous cylindrical source of diameter R at time t:

$$T-T_o = \frac{qt}{\rho c}(1-e^{-R^2/4at}) - \frac{qR^2}{4\lambda}E_i(-R^2/4at) \qquad (6)$$

where λ=thermal conductivity(J/smm^oC).
For q it is noted that:

$$q = \frac{JA}{n\pi R^2} E \qquad (7)$$

where J=current density related to the electrode surface(A/mm^2), A=electrode surface(mm^2),n=number of emitting peaks.
For small values of $R^2/4at$ it is possible to reduce the exponential integral in eq.6 to a series.Then,after substituting eq.7 in eq.6:

$$EJ = \frac{4\pi n\lambda(T-T_o)}{(\gamma-\ln R^2/4at)A} \qquad (8)$$

where γ is Euler's constant.
The value of n can be obtained by registration of the roughness profile.It was approx.200 for all four roughnesses(apparently the number of emitting peaks is constant,but the emitting surface per peak is dependent on the roughness).
From n and the values of the total emitting surface given in section 5,R^2 can be calculated.For t=5.3μs(the ignition delay in the marked points of the figs.3,4,5,6),after substituting n, R^2,A and the material constants of hexane in eq.8,with T = $T_{boiling}$,for EJ:10.0,10.5,10.9 and $11.5\cdot10^{-3}$ J/mm^{3}s are obtained for roughnesses 5,75,125 and 200Ru,respectively.
The values belonging to the marked points in the figs.3,4,5,6 are:8.1,10.0,8.6 and $7.1\cdot10^{-3}$ J/mm^{3}s,respectively.

7. Concluding remarks

In the preceding sections,starting from a number of experiments, a thermal model for the breakdown mechanism of liquids was deduced.The model and the experiments show a good agreement.
Further research will be directed on a number of related subjects (such as the origin of the measured currents) before investigating the influence of impurities on the breakdown mechanism.
A good knowledge of the breakdown mechanism in EDM is necessary to come to a considered choice of the liquids to be used;this is important for the efficiency of EDM.Besides,it appeared that the ignition delay depends on the energy per unit volume added to the gap;this implies that the ignition delay is strongly dependent on the gap width.Therefore it would be better to use the ignition delay as a sensor for the servo-system instead of the the voltage drop across the electrodes.Investigations in this field are being carried out in our laboratory.

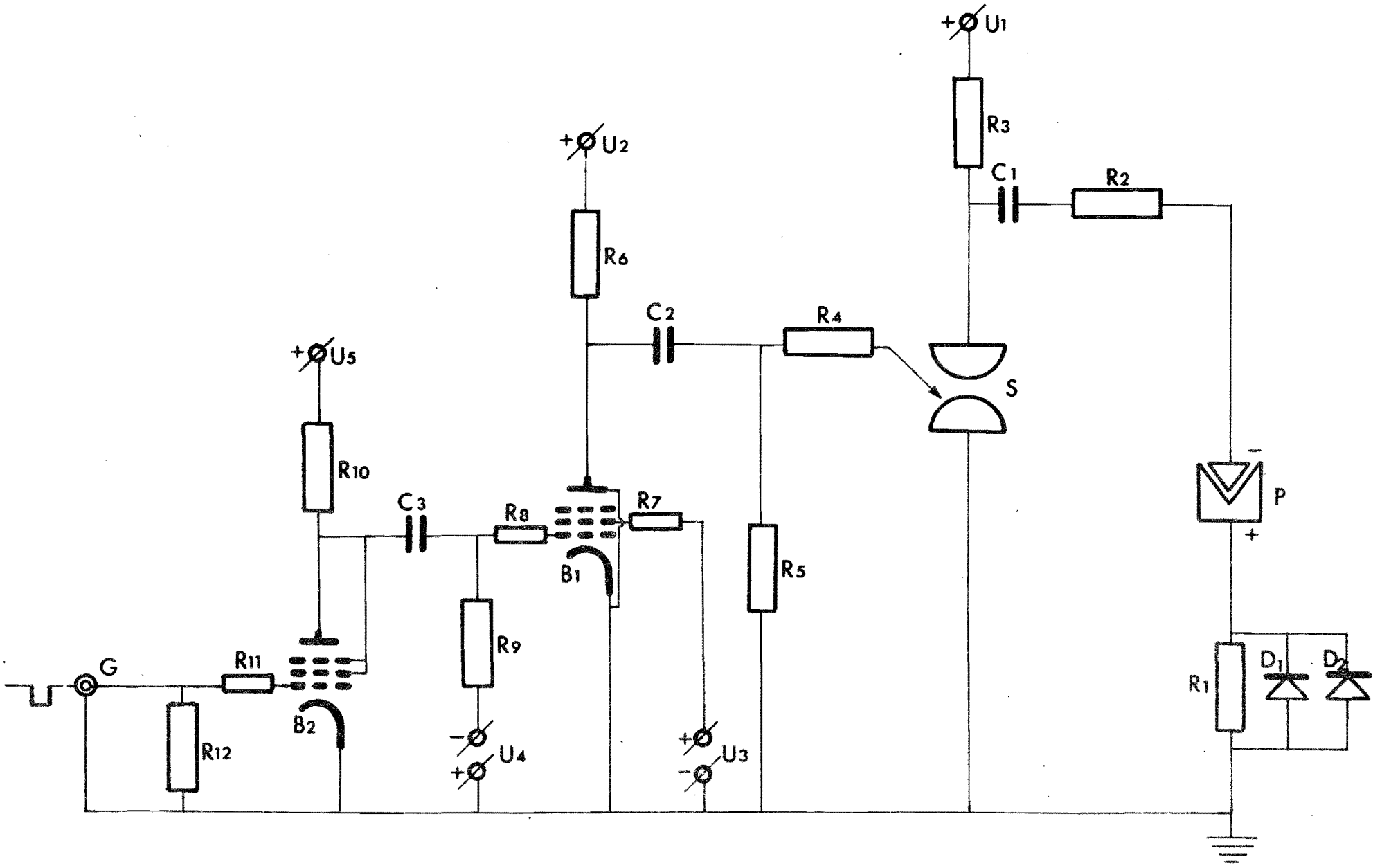

fig.1 Pulse generator for producing single pulses

P : test cell

G : pulse generator

S : high voltage air gap-switch

B_1 : penthode PL 504

B_2 : ,, EL 86

D_1 : diode IN 914

D_2 : ,, BXY 30/500

C_1 : capacitor 1 nF

C_2 : ,, 10 nF

C_3 : ,, 10 nF

R_1 : resistor 10 k

R_2 : ,, 3x33 k Ω serie (½W)

R_3 : ,, 10x100k Ω serie (½W)

R_4 : ,, 10x 1 k Ω serie (½W)

R_5 : ,, 47 k Ω

R_6 : ,, 100 k Ω

R_7 : ,, 100 Ω

R_8 : ,, 100 Ω

R_9 : ,, 100 kΩ

R_{10} : ,, 10 kΩ

R_{11} : ,, 100 Ω

R_{12} : ,, 56 Ω

U_1 : gap-voltage, 3 to 20 kV

U_2 : anode voltage of tube PL 504, 2.5 kV

U_3 : screen grid voltage of tube PL 504, 270 V

U_4 : control grid voltage of tube PL 504, -80 V

U_5 : anode voltage of tube EL 86, 270 V

Explanation of the symbols used in fig.1

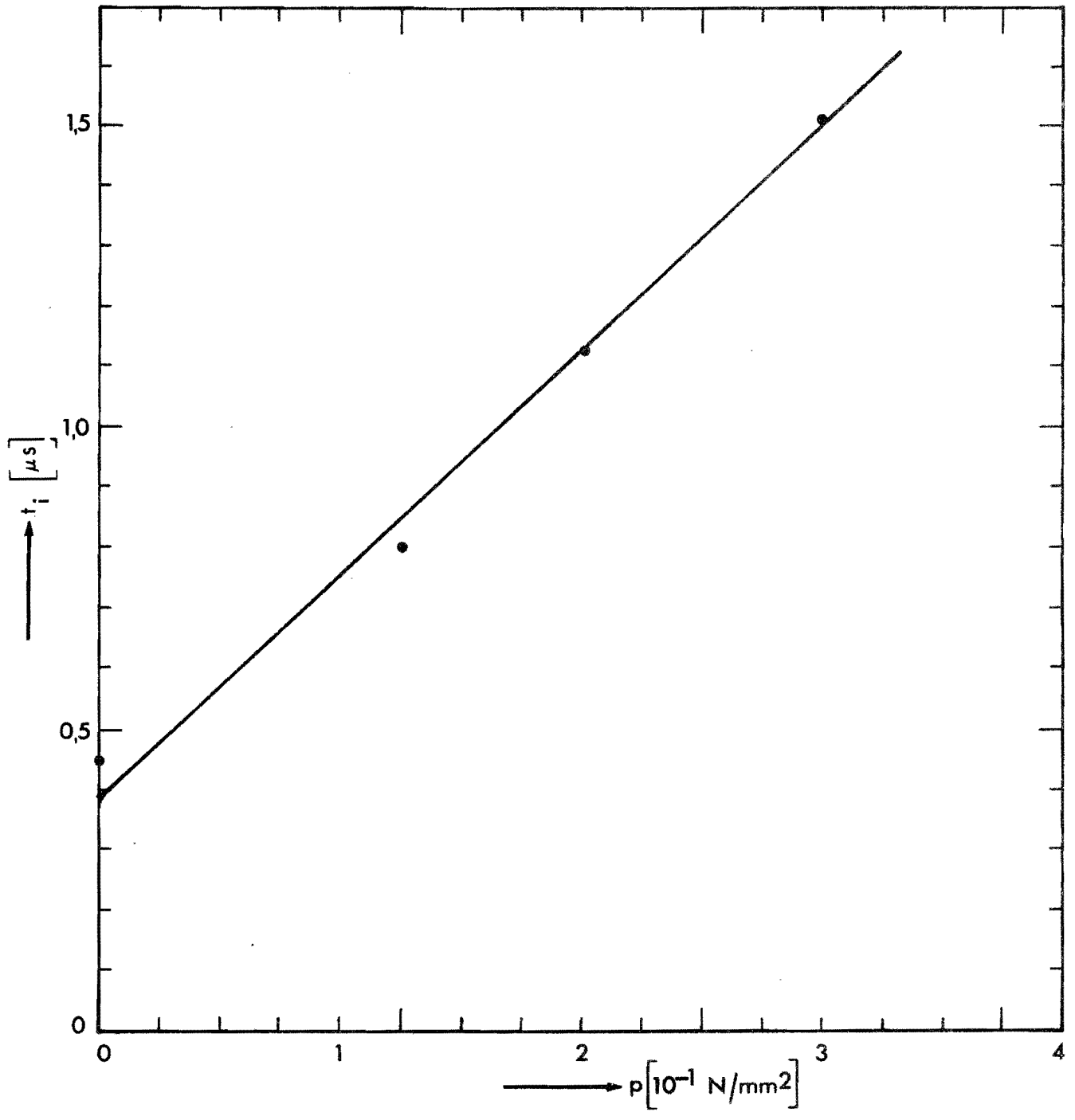

fig.2 The ignition delay as a function of the pressure above atmospheric. Gap width: 40μm; gap voltage: 3800V; cathode: electrolytic copper; anode: electrolytic copper; roughness of the electrodes: 60Ru.

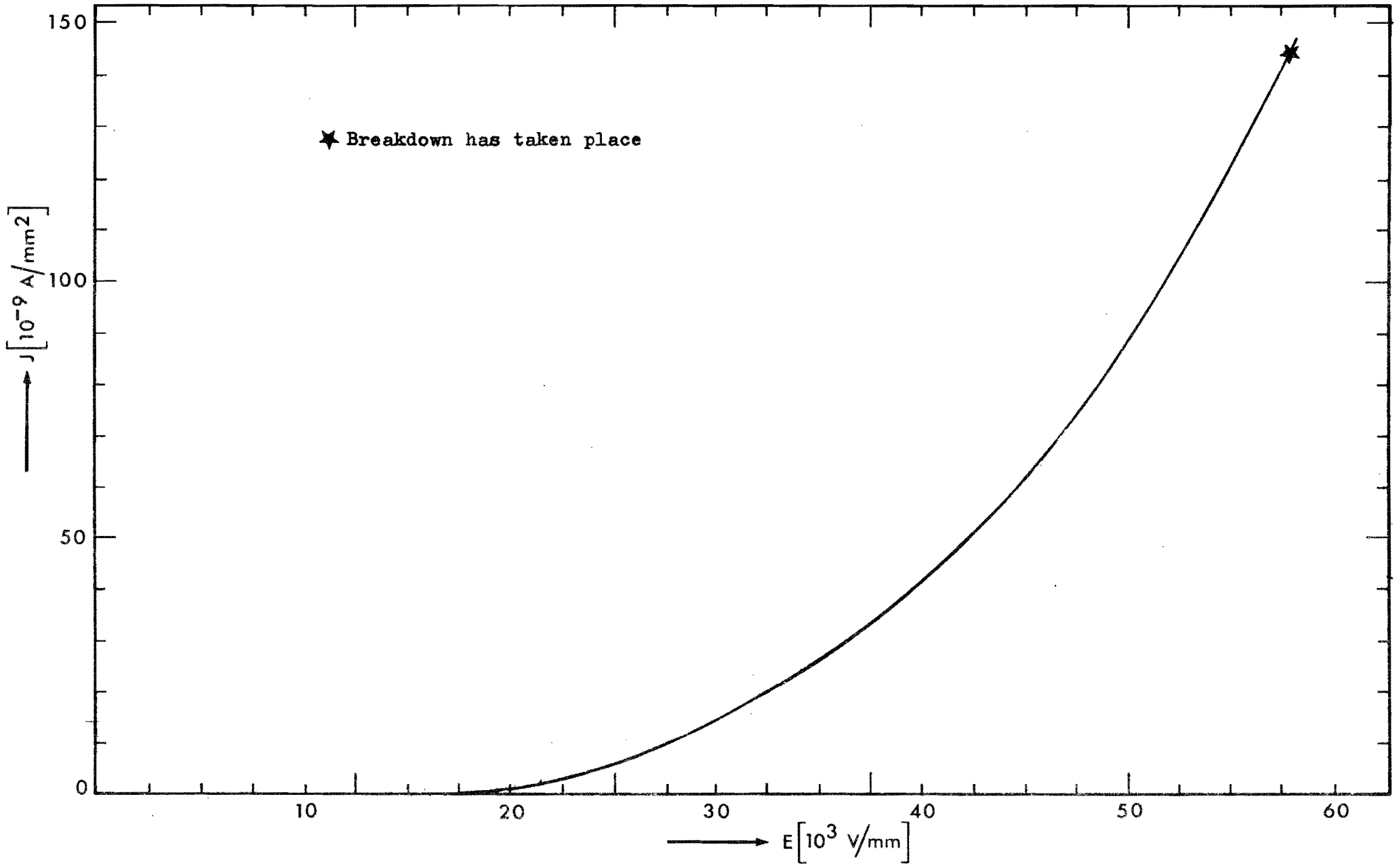

fig.3 The current density as a function of the field intensity. Roughness of the electrode surface:5Ru.

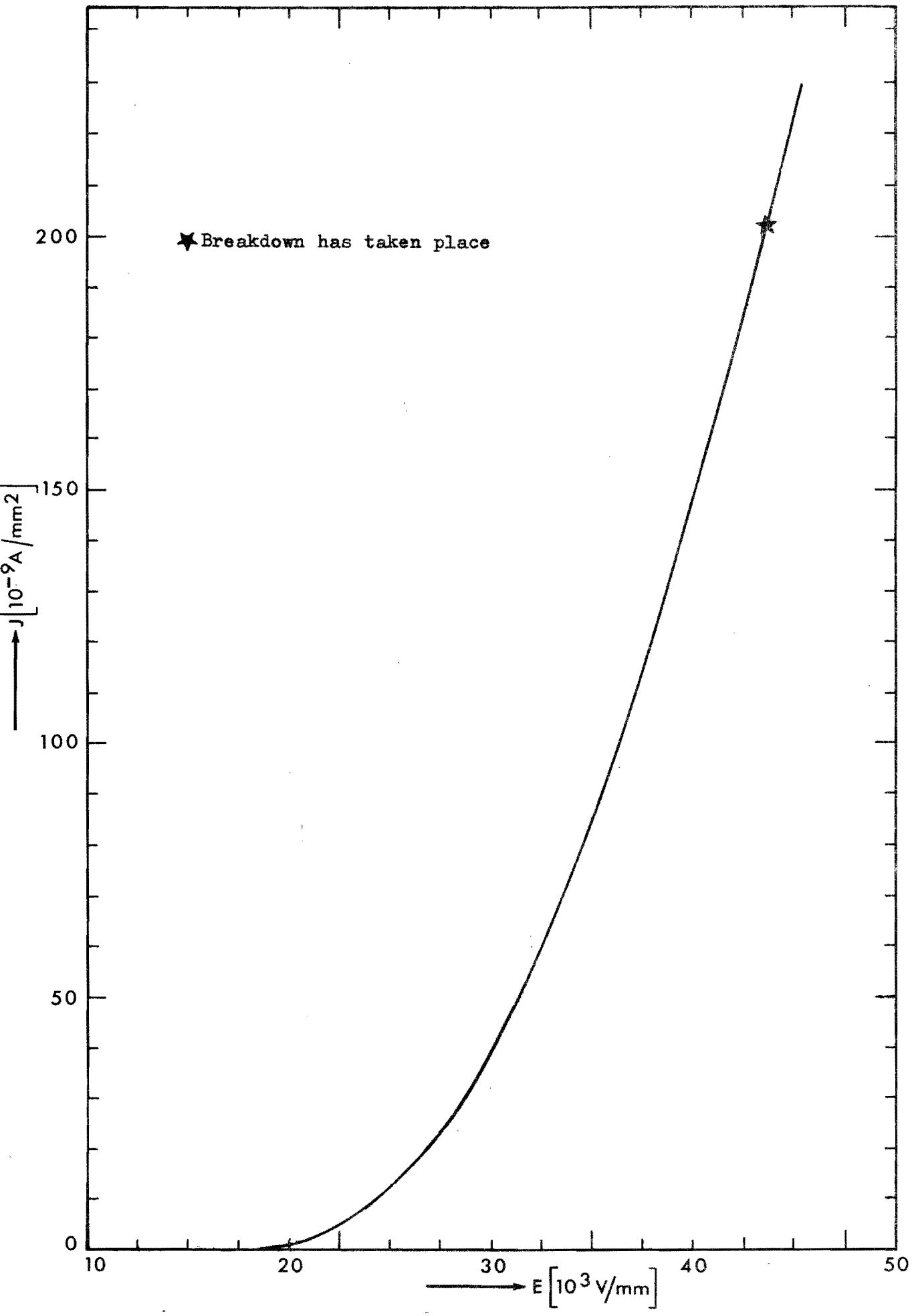

fig.4 The current density as a function of the field intensity. Roughness of the electrode surface: 75Ru.

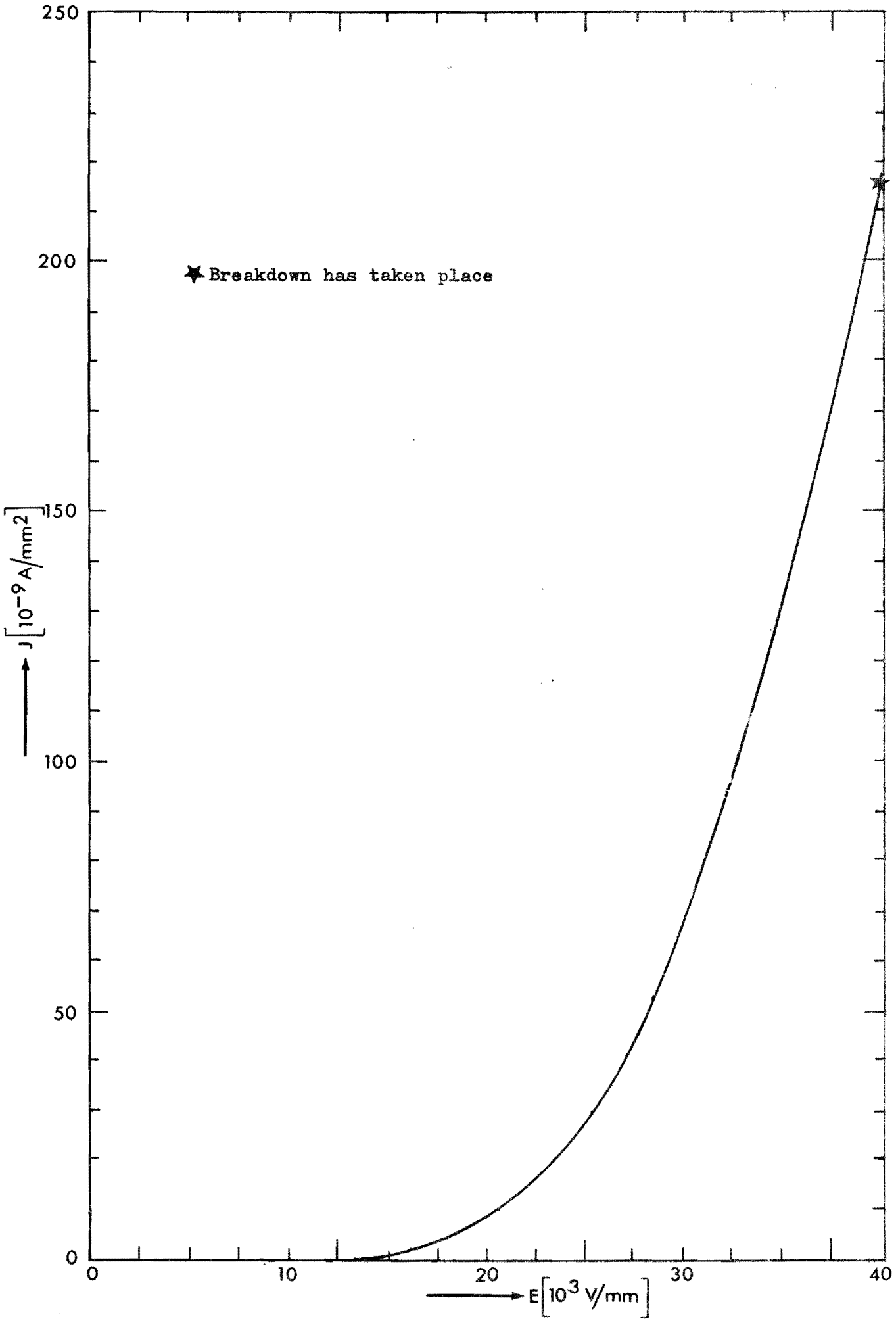

fig.5 The current density as a function of the field intensity. Roughness of the electrode surface: 125Ru.

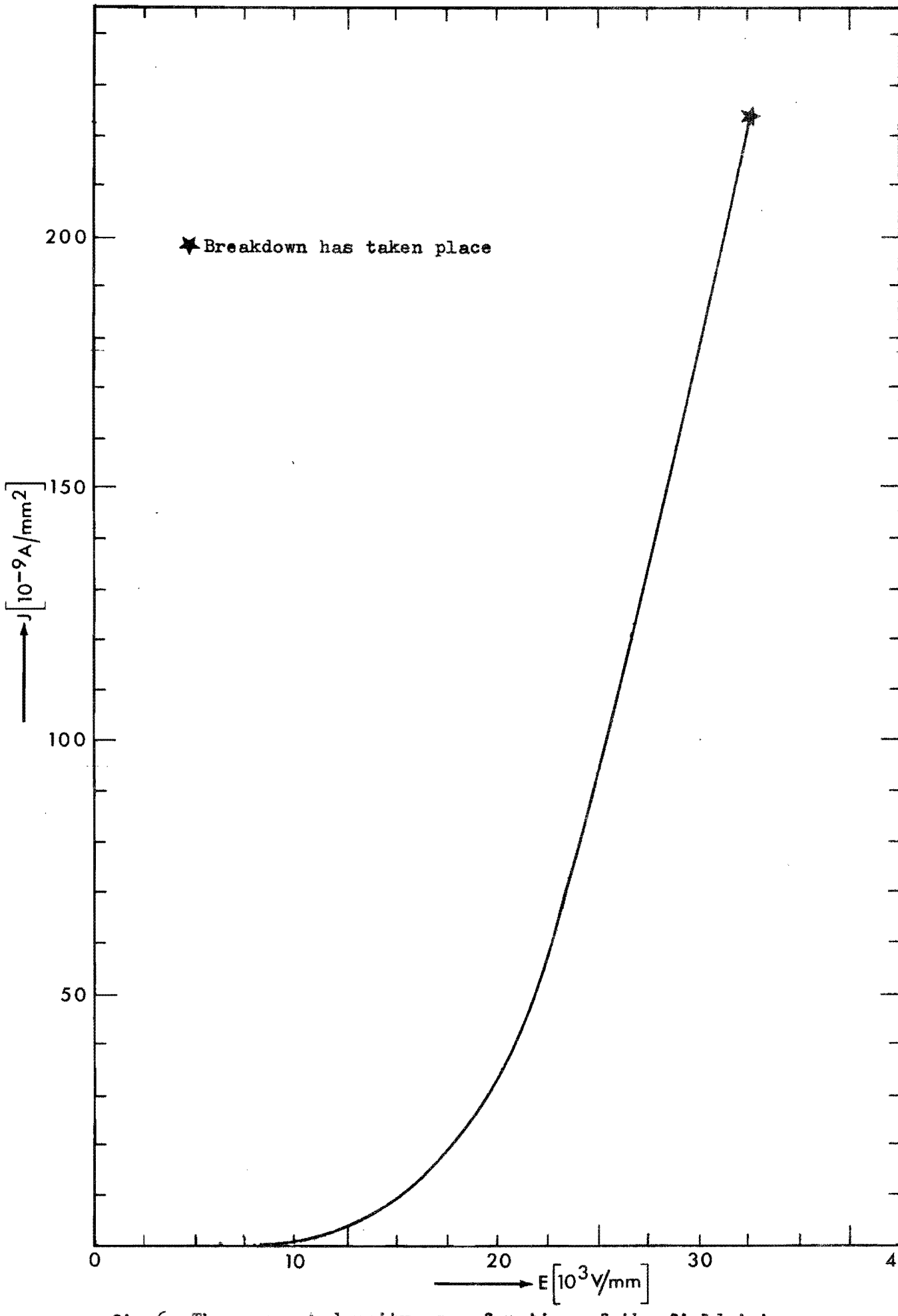

fig.6 The current density as a function of the field intensity. Roughness of the electrode surface: 200Ru.

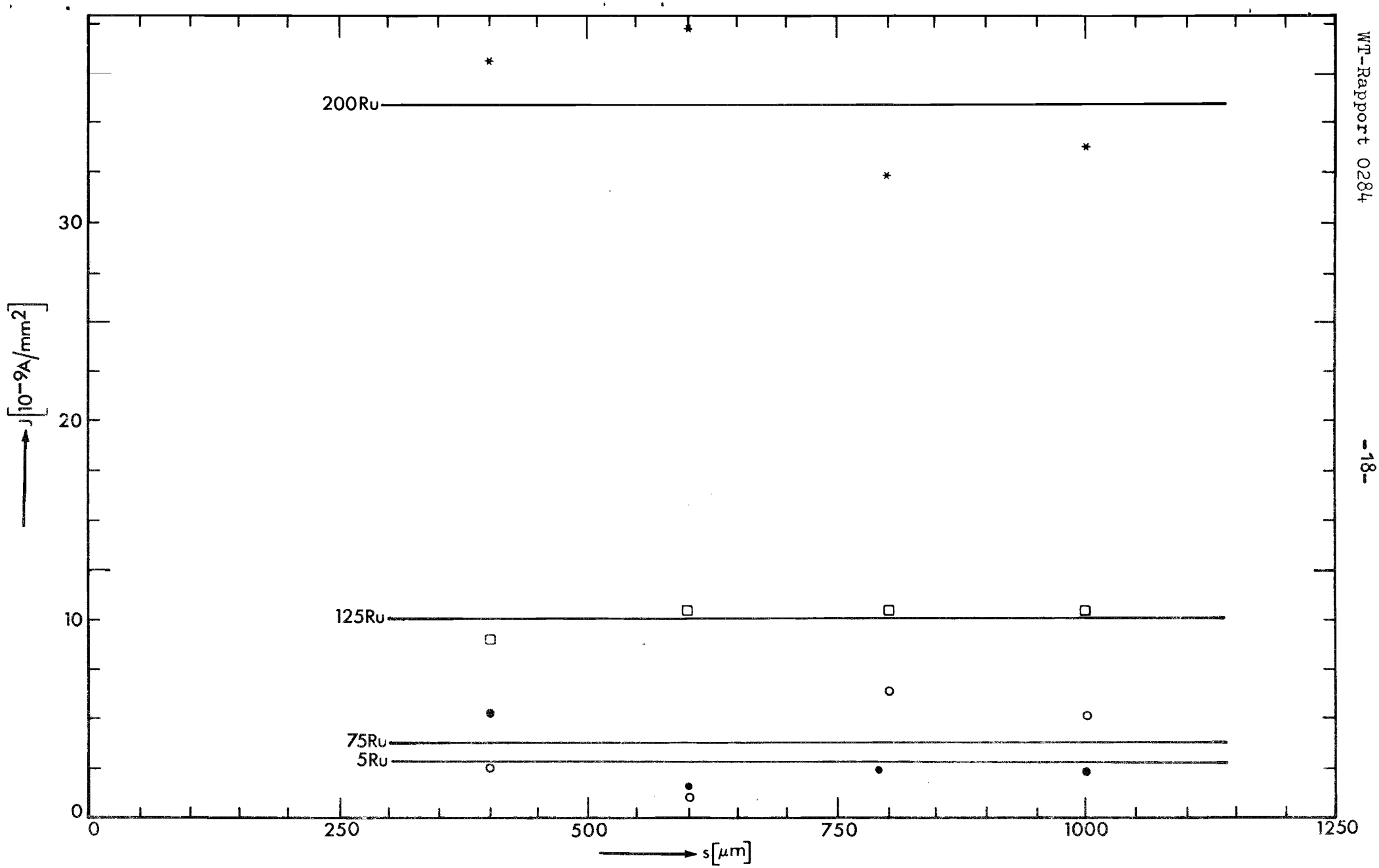

fig.7 The current density as a function of the gap width at constant field intensity($E=2.10^4 V/mm$), with the roughness of the electrode surface as parameter.

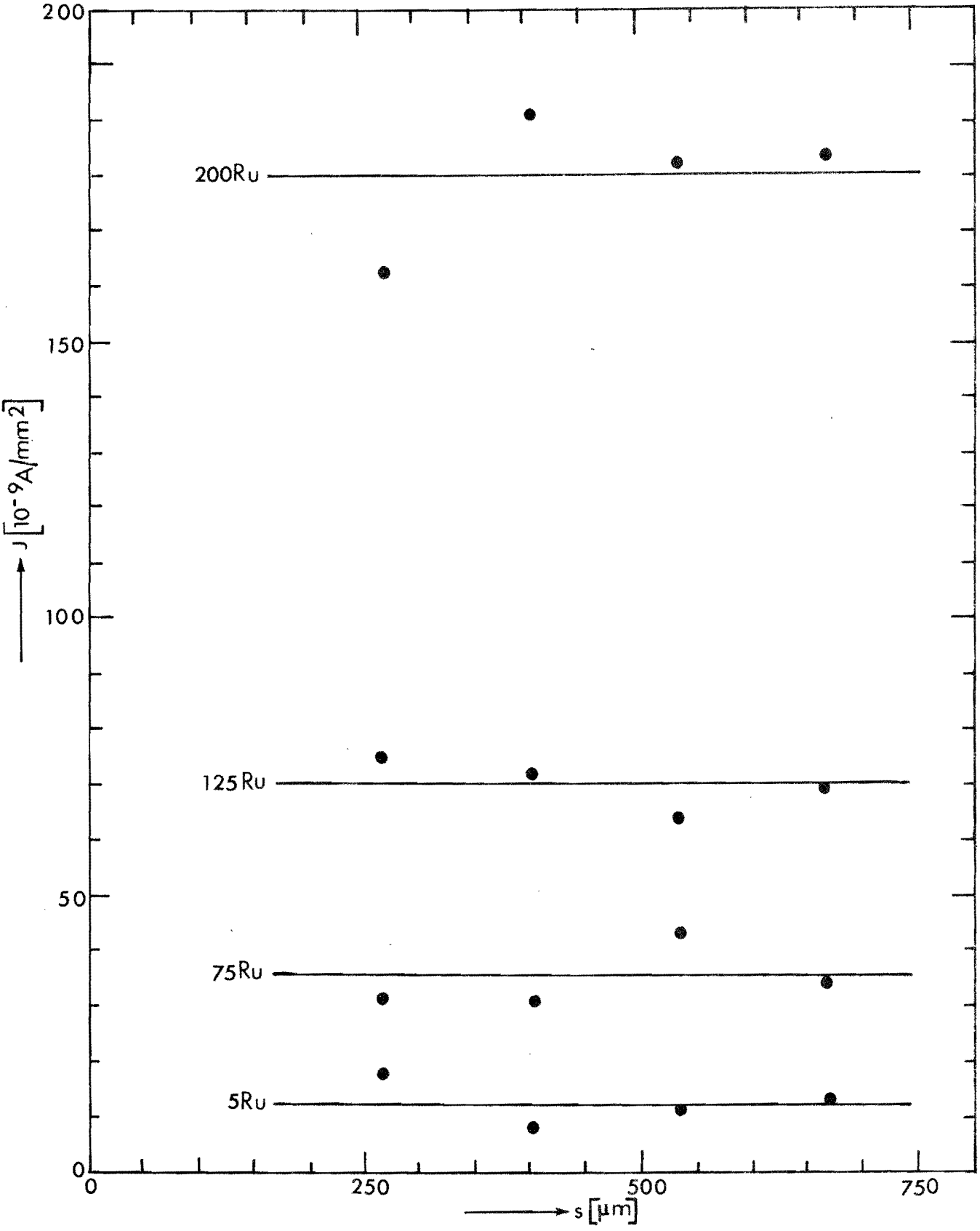

fig.8 The current density as a function of the gap width at constant field intensity($E=3.10^4$V/mm), with the roughness of the electrode surface as parameter.

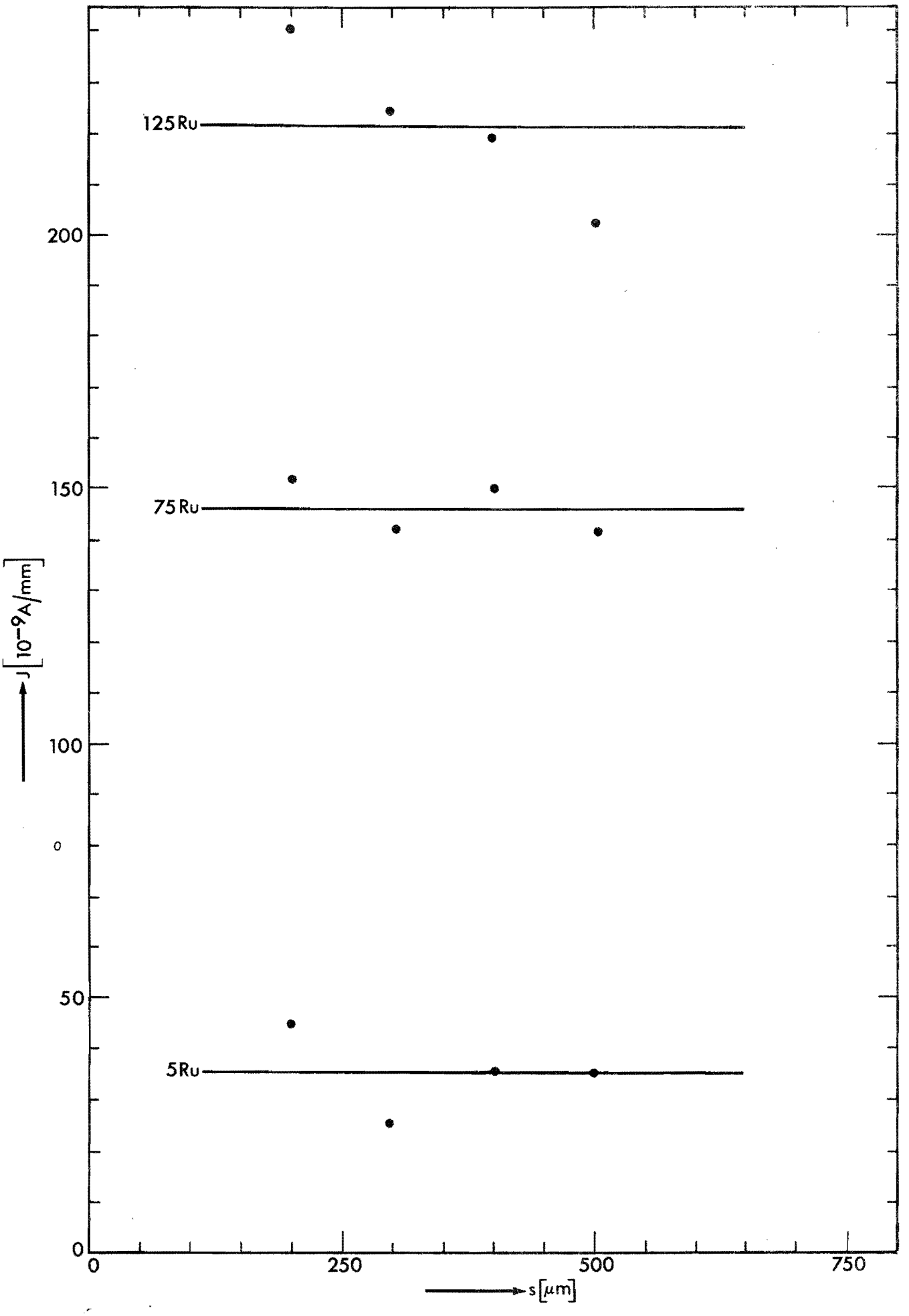

fig.9 The current density as a function of the gap width at constant field intensity($E=4 \cdot 10^4 V/mm$), with the roughness of the electrode surface as parameter.

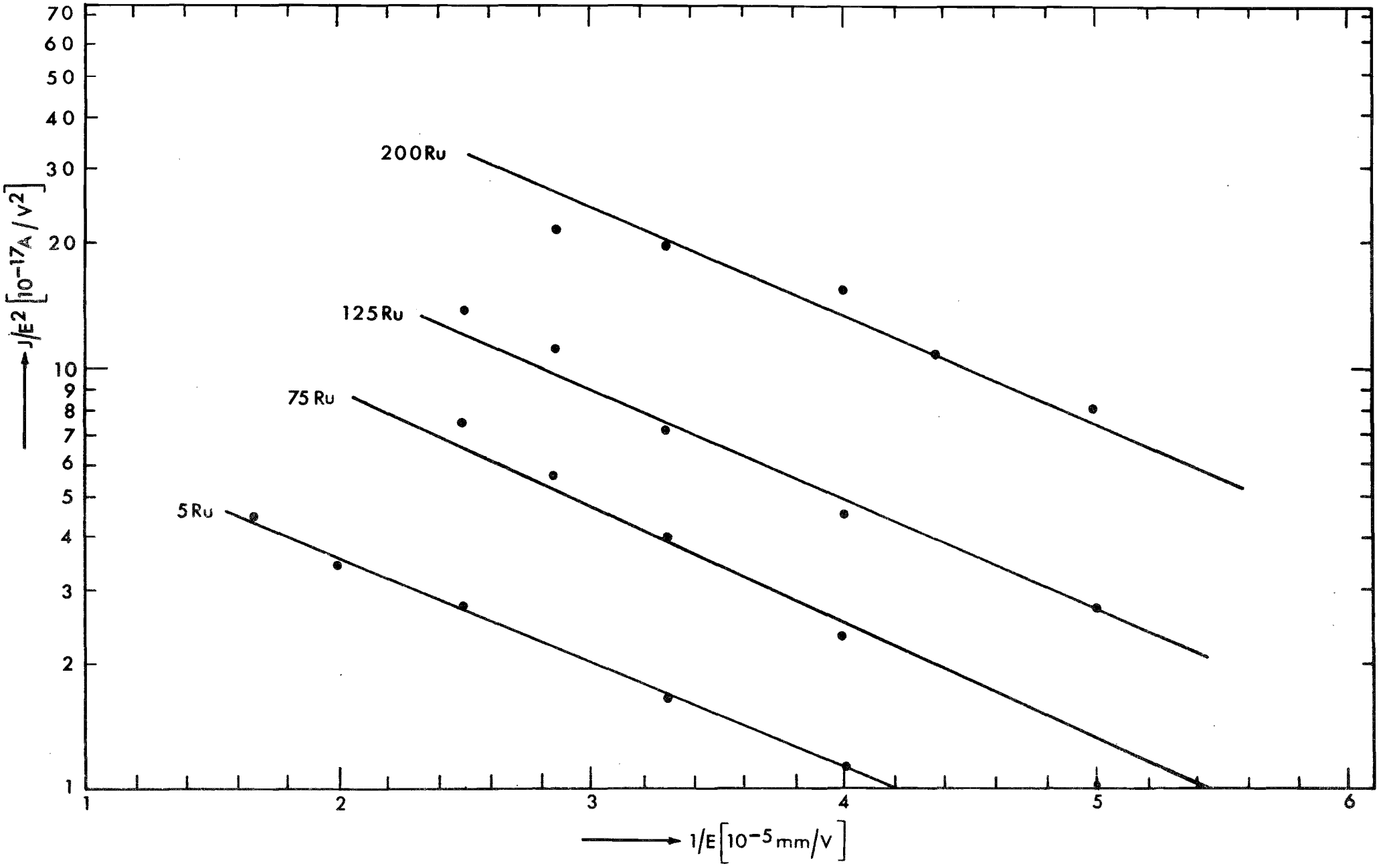

fig.10 J/E^2 as a function of 1/E (logarithmic), with the roughness of the electrode surface as parameter.

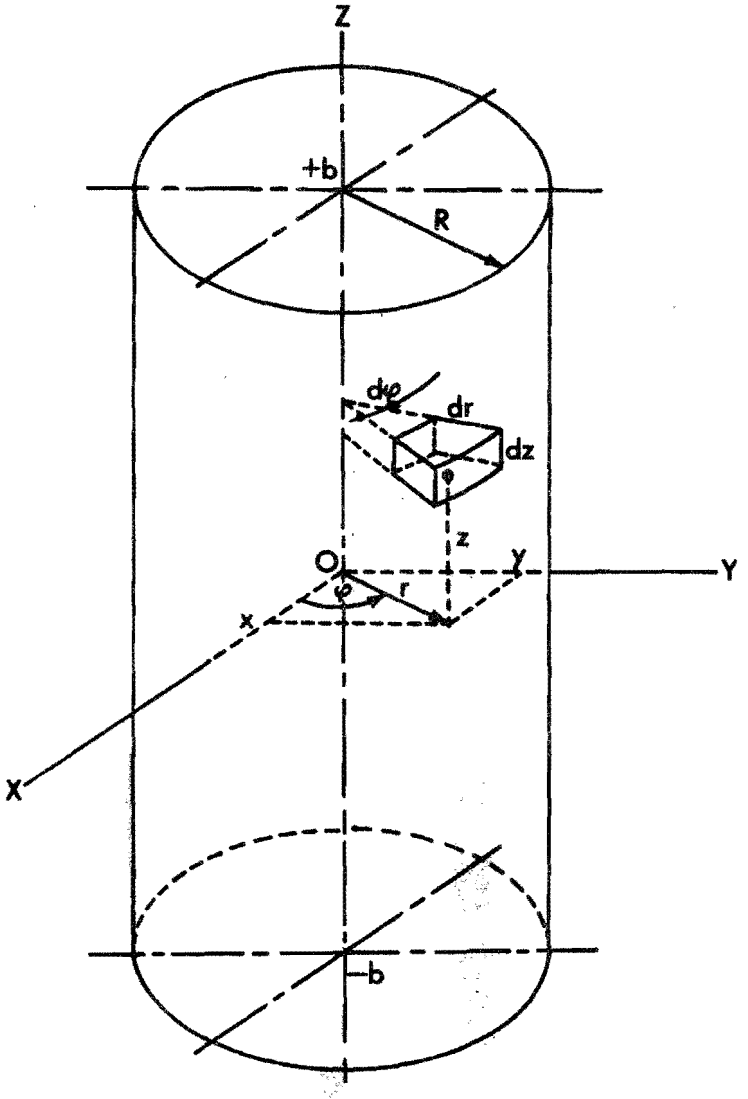

fig.11 Coordinate system belonging to the model.

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