GEOMETRIC EFFECTS CONTRIBUTING TO ANTICIPATION OF THE BEVEL EDGE IN SPREADING RESISTANCE PROFILING

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When spreading resistance probings are made prior to the bevel edge, the data values obtained are generally ignored in subsequent processing. On bare surfaces, though, the increase in measured resistance often observed as the bevel is approached, is meaningful and may be a cause of concern. One of the sources of this increase, referred to here as “anticipation of the bevel edge” is due to a geometric effect: the truncation of part of the conductive layer by the bevel. Under worst-case conditions, the geometric effect will increase measured resistance by a factor of two — insufficient to account for the order of magnitude increase observed on some ultra-shallow profiles. In an effort to separate the geometric effect from other causes, we calculate its magnitude from a simple image model. The calculations show the geometric effect is minimized with close probe spacing and shallow bevel angles, and provide guidelines for choosing suitable bevel angle and spacing.

In figure 1, an illustration of spreading resistance probings starting on the original surface of a beveled silicon sample is shown. If the surface is bare and the top conductive layer is thin enough, the spreading resistance measurements obtained on the original surface often increase in value as the bevel edge is approached. In figure 2, the expected resistance values for a 1000Å junction are shown. The increases in resistance shown were based only on a geometric effect — the truncation of part of the conductive layer by the bevel. Note the magnitude of the increase is greater when a steeper bevel angle is used.

Other effects such as carrier spilling and possible bevel surface damage are not considered here although they are important and in some cases, of greater consequence. In this figure and the subsequent ones, a Gaussian distribution, a surface concentration of 1×10^{20} cm^{-3}, a background concentration of 1×10^{15} cm^{-3} , and a probe contact radius of one micron are assumed.

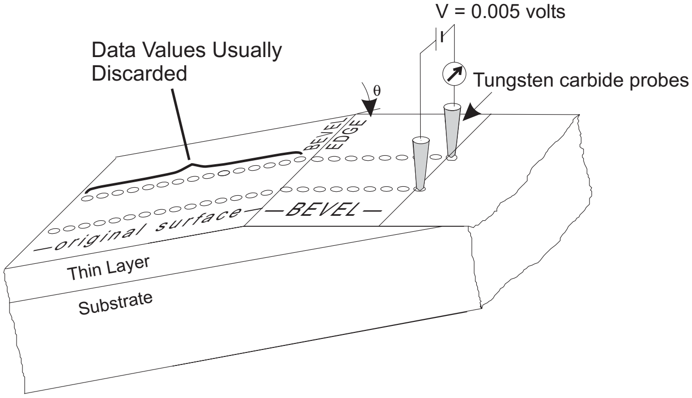


Figure 1 — An illustration of spreading resistance profiling on a beveled sample. (The bevel angle is often much smaller than indicated.)

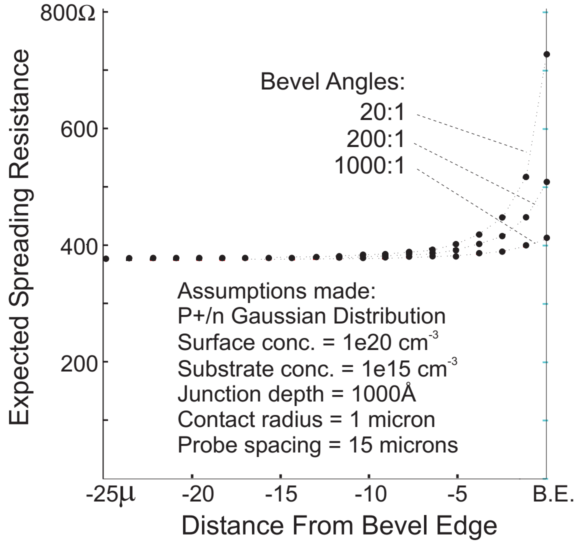


Figure 2 — Calculations for the geometric effect indicate an increase in resistance as the bevel edge is approached.

In figure 3, the probe spacing is varied. Note increasing the probe spacing increases the measured resistance and the anticipation of the bevel edge. In figure 4, the junction depth is varied while maintaining the surface concentration at 1e20 cm^{-3}. A layer with a thinner junction will then have fewer carriers/cm^{2} and have higher measured resistance. Note the anticipation of the bevel edge becomes greater as the junction becomes more shallow.

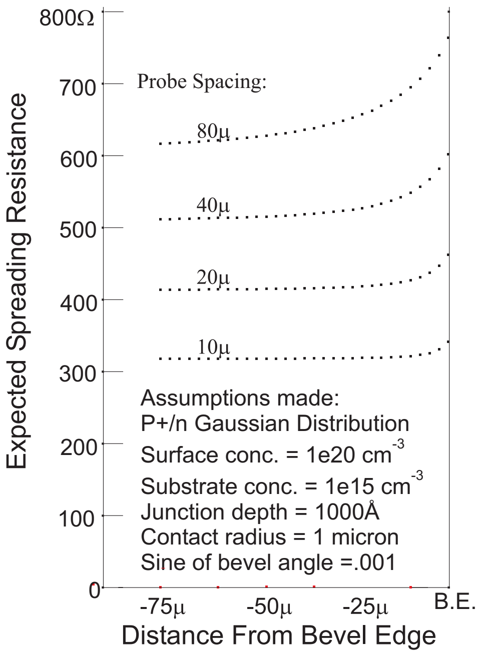


Figure 3 — Calculations for the geometric effect indicate an increase in anticipation of the bevel edge for wider probe spacings.

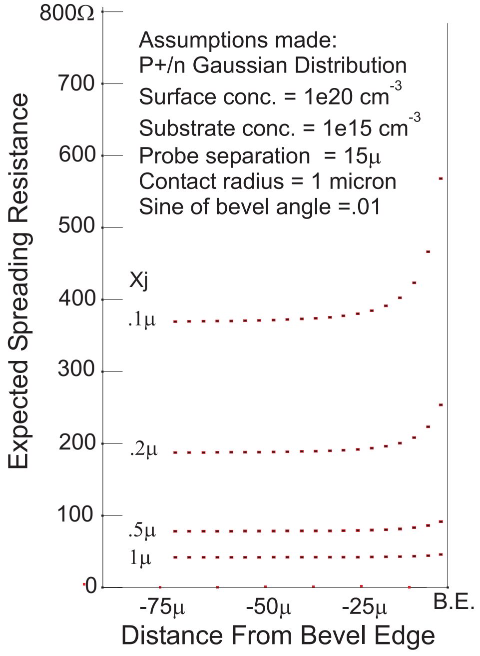


Figure 4 — Calculations for the geometric effect indicate an increase in anticipation of the bevel edge for more shallow structures.

The change in resistance is affected by the junction depth, bevel angle and probe spacing. Fortunately, the bevel angle and junction depth can be linked to another value already appreciated by the spreading resistance analyst — the on bevel distance to the junction, Xj/sin(bevel angle). Also, it may be useful to consider normalized resistance values at the bevel edge, R_{BE}/R_{NB} where R_{BE} is the calculated resistance at the bevel edge and R_{NB} is the calculated resistance with no bevel (or probings made an infinite distance from the bevel edge). In figure 5, the anticipation of the bevel edge is plotted as R_{BE}/R_{NB} and compared to the on bevel distance to the junction. We believe this chart may serve as a guideline for estimating the severity of anticipation of the bevel edge due to the geometric effect and choosing suitable bevel angle and spacing. In general, geometric considerations encourage smaller bevel angles and larger stepping increments.

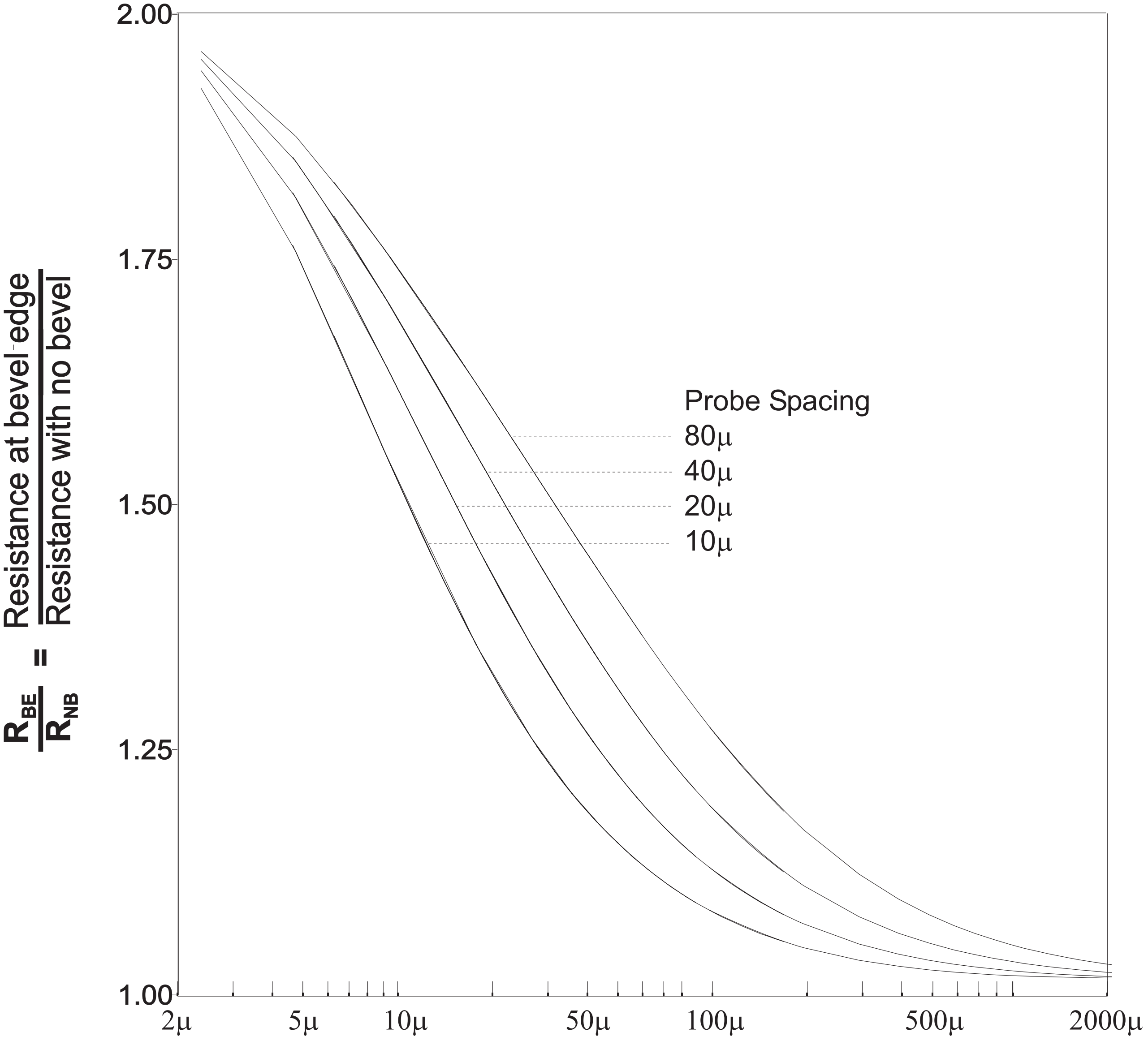


Figure 5 — A guideline to anticipation of the bevel edge due to the geometric effect as a function of bevel length to the junction and probe spacing.

CALCULATIONS

The conductive layer is divided into 100 sub-layers. Figure 6 illustrates the 2 sub-layers nearest the surface. The distance from the probe to the bevel edge is given as L_0. The distance from the probe to the edge of the first sub-layer is $L_0 + t/\sin\theta$ where t is the thickness of the sub-layer and θ is the bevel angle. (The magnitude of the bevel is greatly exaggerated in the figure.) The distance from the probe to the edge of the jth sub-layer is $L_0 + j \cdot t/\sin\theta$. To facilitate understanding, the diagram in figure 5 is redrawn in figure 6 to align the original surface to the horizontal and to replace the bevel with steps. Clearly, one would expect the resistance of a sub-layer to increase as t/sinθ decreases. The value t/sinθ can be increased (and anticipation of the bevel edge reduced) if it is possible to reduce θ, the bevel angle.

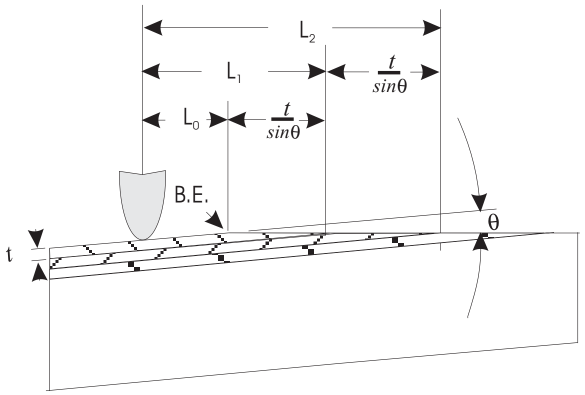


Figure 6 — Illustration of the spreading resistance probe approaching the bevel edge. The thin layer has been divided into 100 sub-layers, with only the first three shown. The probe's current lines are limited only by the bevel.

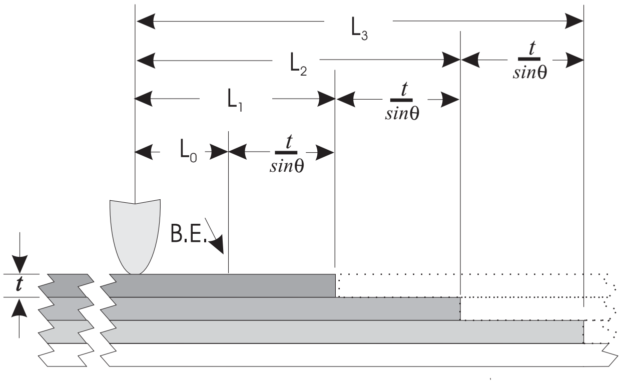


Figure 7 — A simplification of the previous figure. The original surface was positioned on the horizontal and the bevel was replaced by descending steps. The missing portion of each sub-layer reduces the conduction and increases the resistance.

When the probes are several probe spacings from the nearest edge, the measured resistance is:

$$R = \frac{\rho}{\pi t} \ln \frac{s}{a} \qquad \text{(Equation 1)}$$

where: R is the measured resistance in ohms
(hereafter called "R_{NB}" for "R no bevel")
ρ is the resistivity in ohm-cm
s is the probe spacing
a is probe contact radius (assumed to be 1μ)
t is the layer thickness in cm.

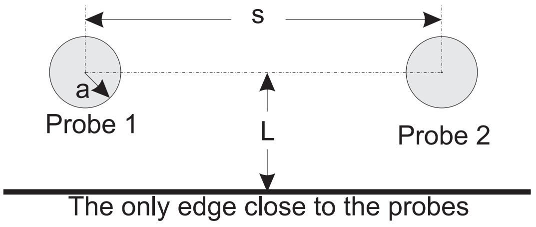


Figure 8 — Illustration of the spreading resistance probes near one edge. When L is very large, R can be found by using equation 1. As L→ 0, R reaches a limit of twice the resistance calculated from equation 1. For other values of L, equation 2 should be used.

When the probes are a distance L from one edge but several probe spacings from other edges (see figure 8), the measured resistance is:

$$R = \frac{\rho}{\pi t} \ln\left[\frac{s}{a} \cdot \frac{\sqrt{s^2 + 4L^2}}{2L}\right] \qquad \text{(Eq. 2)}$$

As $L \rightarrow \infty$, $R \rightarrow R_{NB}$ and by inspection, $R \rightarrow 2R_{NB}$ as $L \rightarrow 0$.

Resistivity values were calculated after Thurber *et al.*(3)+ using concentration values determined from the Gaussian distribution

$$C(x) = Cs \exp\left[\frac{-X^2}{4DT}\right] \quad \text{and } DT = \frac{Xj^2}{4\ln\frac{C_S}{C_B}}$$

where: C(x) is the concentration at depth X
C_S is the surface concentration set at 1×10^{20} cm^{-3}
X is the depth in cm.
DT is the product of the diffusivity and the time (calculated from Xj, C_S, and C_B)
Xj is the junction depth in cm.
C_B is the background concentration set at 1×10^{15} cm^{-3}

A p-type layer over an n-type substrate was assumed. Since the surface concentration is 5 orders of magnitude higher than background, the conductance lost due to the depletion region was considered negliable. A Gaussian distribution with a surface concentration of 1×10^{20} cm^{-3} was used believing this caused worst-case anticipation of the bevel edge among the commonly occurring ultra-shallow profiles. Some calculations were done assuming a complementary error function and surprisingly little increase in the anticipation of the edge was noted. Also, some calculations were done assuming $C_S = 1 \times 10^{18}$ cm^{-3} with surprisingly little decrease in anticipation of the bevel edge.

SUMMARY

The geometric contribution to anticipation of the bevel edge in spreading resistance profiling was discussed. Calculations based on a simple image model were used to determine its magnitude. Shallow bevel angles and closely spaced probes help reduce its effect. Under worst-case conditions, the geometric effect will increase the measured resistance by a factor of two — insufficient to account for the order of magnitude increases in measured resistance that have been observed on some ultra-shallow profiles. A Gaussian profile with a surface concentration of 1×10^{20} cm^{-3} was used. Bevel angle, probe spacing, and junction depth were varied. The relationship we found most useful was R_{BE}/R_{NB} plotted against the on bevel distance to the junction. In worst-case structures, the same considerations suggest that measured resistance on the bevel must be corrected for the geometric effect.

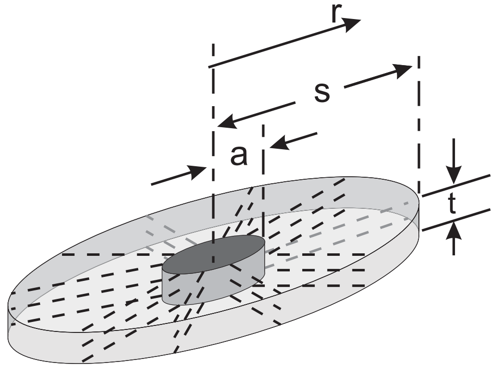
REFERENCES

1. D. H. Dickey and J.R. Ehrstein, NBS Special Publication 400-48, pp. 15-18 (May 1979).

2. D. H. Dickey, ICSIT '92 Conference, Tokyo, November 10, 1992.

3. Thurber, Mattis, Liu, and Filliben, NBS Special Publication 400-64, Table 10, p 34 and Table 14, p40.

APPENDIX



Development of the Simple Image

From thin conductive layers, the probe contact is assumed to be a cylinder of radius a and height t. Current is assumed to flow radially from the sides of the cylinder to the edges of the layer. The incremental resistance dR from r to dr can be expressed as the product of the resistivity and incremental length dr divided by the cross sectional area 2πrt or:

$$dR = \frac{r\,dr}{2\pi r t}$$

Appendix (continued)

Then, the resistance R from the edge of a cylinder of radius a through the conductive layer to a distance s from the centerline of the probe contact can be expressed as:

$$R = \frac{\rho}{2\pi t}\int_a^s \frac{dr}{r} = \frac{\rho}{2\pi t}\ln\frac{s}{a}$$

If a potential V is applied to the probe causing a current I, then potential at s will be $V = \frac{I\rho}{2\pi t}\ln\frac{s}{a}$

A second probe (P2) with a potential -V is positioned a distance s from the first probe (P1).

The potential -V on P2 causes a current -I producing a potential $-V + \frac{I\rho}{2\pi t}\ln\frac{s}{a}$ at P1.

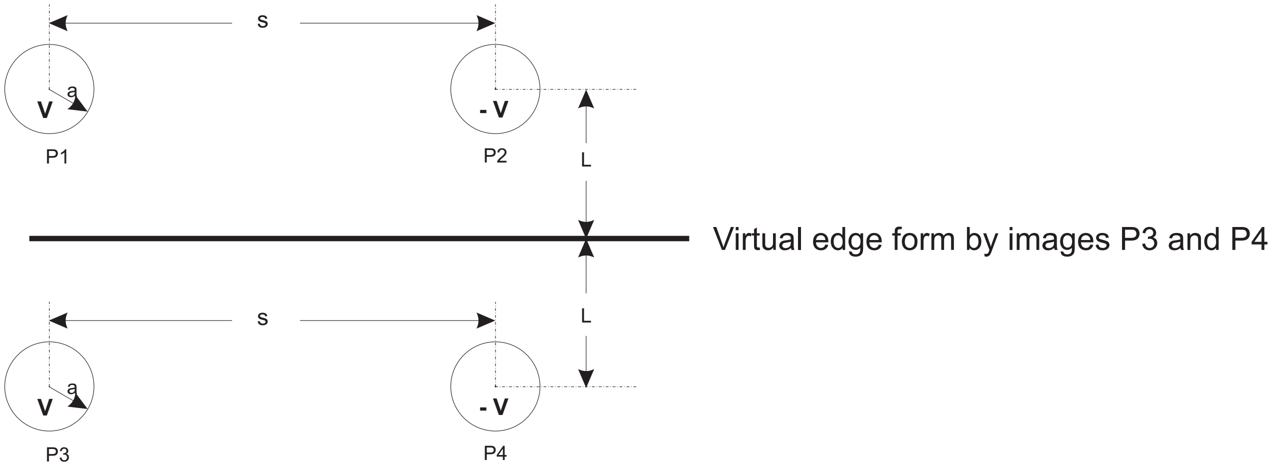
Summing the potential at P1, $V1 = +V - V + \frac{I\rho}{2\pi t}\ln\frac{s}{a} = \frac{I\rho}{2\pi t}\ln\frac{s}{a}$

Summing the potential at P2, $V2 = -V + V - \frac{I\rho}{2\pi t}\ln\frac{s}{a} = -\frac{I\rho}{2\pi t}\ln\frac{s}{a}$

The potential difference between P1 and P2 = $V1 - V2 = \frac{I\rho}{2\pi t}\ln\frac{s}{a} - -\frac{I\rho}{2\pi t}\ln\frac{s}{a} = \frac{I\rho}{\pi t}\ln\frac{s}{a}$

Dividing by I, the resistance between the probes is , $R = \frac{V1 - V2}{I} = \frac{\rho}{\pi t}\ln\frac{s}{a}$ (Equation 1)

At a distance 2L, add images P3 and P4 applying potentials +V and -V respectively.
This simulates an edge (end of the conductive layer) a distance L from probes P1 and P2.



Appendix (continued)

The potential at P1 due to P2 is $-V + \frac{I\rho}{2\pi t}\ln\frac{s}{a}$

The potential at P1 due to P3 is $+V - \frac{I\rho}{2\pi t}\ln\frac{2L}{a}$

The potential at P1 due to P4 is $-V + \frac{I\rho}{2\pi t}\ln\frac{\sqrt{s^2+4L^2}}{a}$

Summing the potential at P1, $V1 = +V - V + \frac{I\rho}{2\pi t}\ln\frac{s}{a} + V - \frac{I\rho}{2\pi t}\ln\frac{2L}{a} - V + \frac{I\rho}{2\pi t}\ln\frac{\sqrt{s^2+4L^2}}{a}$

$$V1 = \frac{I\rho}{2\pi t}\left[\ln\frac{s}{a} + \ln\frac{\sqrt{s^2+4L^2}}{a} - \ln\frac{2L}{a}\right] = \frac{I\rho}{2\pi t}\left[\ln\frac{s}{a} + \ln\frac{\sqrt{s^2+4L^2}}{2L}\right]$$

The potential at P2 due to P1 is $V - \frac{I\rho}{2\pi t}\ln\frac{s}{a}$

The potential at P2 due to P3 is $+V - \frac{I\rho}{2\pi t}\ln\frac{\sqrt{s^2+4L^2}}{a}$

The potential at P2 due to P4 is $-V + \frac{I\rho}{2\pi t}\ln\frac{2L}{a}$

Summing the potential at P2, $V2 = -V + V - \frac{I\rho}{2\pi t}\ln\frac{s}{a} + V - \frac{I\rho}{2\pi t}\ln\frac{\sqrt{s^2+4L^2}}{a} - V + \frac{I\rho}{2\pi t}\ln\frac{2L}{a}$

$$V2 = \frac{I\rho}{2\pi t}\left[-\ln\frac{s}{a} - \ln\frac{\sqrt{s^2+4L^2}}{a} + \ln\frac{2L}{a}\right] = \frac{I\rho}{2\pi t}\left[-\ln\frac{s}{a} - \ln\frac{\sqrt{s^2+4L^2}}{2L}\right]$$

Then $V1 - V2 = \frac{I\rho}{\pi t}\ln\frac{s}{a} + \ln\frac{\sqrt{s^2+4L^2}}{2L} = \frac{I\rho}{\pi t}\ln\left[\frac{s}{a}\cdot\frac{\sqrt{s^2+4L^2}}{2L}\right]$

The resistance between the probes, $R = \frac{V1 - V2}{I} = \frac{\rho}{\pi t}\ln\left[\frac{s}{a}\cdot\frac{\sqrt{s^2+4L^2}}{2L}\right]$