Measurement of Semiconductor Resistivity using a Four Point Probe

The resistivity , ρ, of a sample is an important parameter, since it can be related to impurity concentration (to characterize a doping process, for example), as well as having direct effects on device performance. A simple, nondestructive way of determining ρ utilizes the <u>four point probe</u>, shown schematically in fig.l. Here four sharply tipped tungsten wires (tungsten is chosen for its hardness) are brought into contact with the semiconductor surface. One immediate problem arises from the contact between the metal and the silicon. At the very least, the Schottky diodes formed there make it impossible to measure resistance using a simple ohm meter and only two connections.

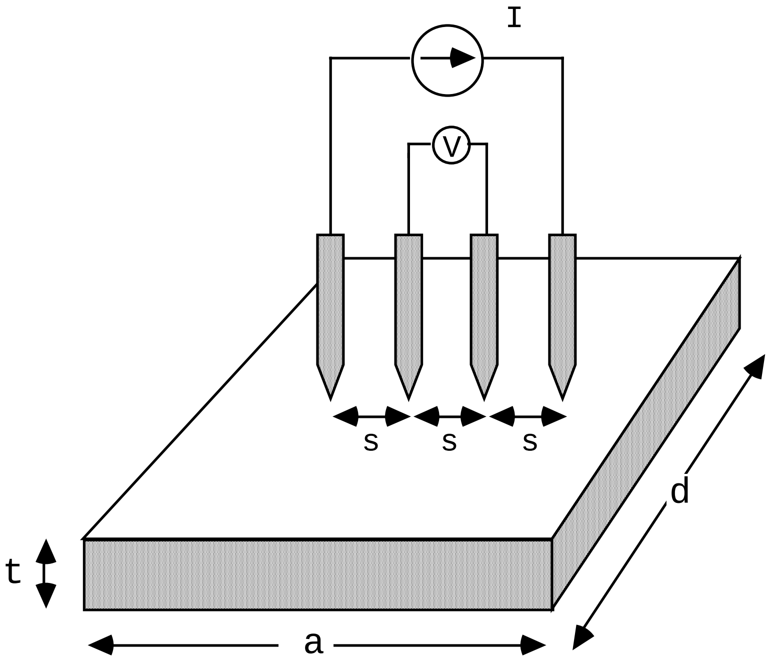

Figure 1: Four point probe; sample dimensions and orientation of probe refer to Table 1.

The four point probe avoids this problem by using a row of four equally spaced needles. A known current is passed between the outer needles, while an open-circuit voltage reading is made between the inner needles. Because no (or very little) current flows through the voltage sensing needles, there are no errors introduced due to the contacts. Of course, there are large voltage drops across the outside needle contacts, but we measure only current in this part of the circuit.

We are faced with another difficulty, however, in extracting the resistivity from the measured I and V. Here the current-carrying probes (outer probes) represent a dipole source, which establishes a field distribution inside the specimen under test. We must solve for the potential difference between the two inner probes under various boundary conditions, set by the sample size and thickness, to derive expressions relating the supplied current, the measured potential difference, and the resistivity of the specimen.

In two limiting cases it is relatively straightforward to find these expressions. For a semi-infinite sample the resistivity is given by

$$\rho = (2\pi s)V/I \qquad (1)$$

where the probes are assumed to be equally spaced by s (ref.1).

The second case is somewhat more useful, the "thin" two-dimensional conducting sheet. Here the current is assumed to be completely confined to a layer t thick, where t is thin, i.e. $t \ll s$. For such sheets it is convenient to define the "Sheet Resistance", R_S, in ohms/square, or $\Omega/\square$. This is simply the resistance of a bar of material of unit length and width, with thickness t. Clearly if t is known, then

$$\rho = R_S t \quad (\Omega\text{-cm}) \qquad (2)$$

and for the two-dimensional sheet (ref. 2),

$$R_S = (\bullet/\mathit{ln}2)V/I = 4.53\ V/I\ (\Omega/\square) \qquad (3)$$

In the case of a sample which has been doped by a diffusion process, the resistivity of the diffused layer is much lower than the substrate, which confines almost all the current to this layer, and the requirement $t \ll s$ is easily satisfied. Also note that since the depth of the diffusion, t, must be determined in some other manner, it is common to give only the sheet resistance, R_S. When t is known eqs 2 and 3 give

$$\rho = 4.53\ t\ V/I \quad (\Omega\text{-cm}) \qquad (4)$$

In the above cases, no edge effects have been considered, and the calculated potential distributions are due to a single dipole source only. For a real sample of finite size, however, the edge effects cannot be ignored. The so-called "diameter" correction factor, CF_d, and "thickness" correction factor, CF_t, have to be considered separately to account for finite sample size. The method of images can be used here to solve for the potential in the presence of finite boundaries. The basic principle is to remove the edges by mirror-imaging the dipole source through the imaginary edge plane, and treat the whole problem in a single medium. As a result, a single dipole source is now replaced by an infinite arrangement of dipoles. Once again, the potential difference between the inner probes due to these infinite dipoles can be solved numerically. The resulting diameter and thickness correction factors are given in tables 1 and 2. The bulk resistivity and sheet resistance for a real sample can thus be expressed in final form as

$$\rho = (V/I)tCF_dCF_t$$

and

$$R_s = (V/I)CF_dCF_t$$

For any epitaxial or diffusion layer in our lab, $t/s<0.5$, and $CF_t=1$. In fact, the thickest conductive layer we encounter is our wafer substrate, $t \leq 0.025"$. Our probe spacing $s = 0.040"$, so even for a bare wafer, $t/s \leq 0.625$, and $CF_t \geq 0.9898$. Note, however, that for many of our samples the diameter correction factor, CF_d, cannot be set to its limiting value of 4.53.

References

1. Valdes, L.G., Proc. I.R.E. Vol. 42, pp. 420-427 (Feb. 1954).

2. Smits, F.M., "Measurements of Sheet Resistivity with the Four-Point Probe," BSTJ, 37, p. 711-718 (1958). (Same as BT Monograph , 3894, Part 2).

3. American Soc. for Testing and Materials, ASTM F 84, Part 43.

Table 1:
Diameter Correction Factor CF_d
(after ref. 2)

		a/d ratio			
d/s	CIRCLE	1	2	3	• 4
1.0				0.9988	0.9994
1.25				1.2467	1.2228
1.5			1.4788	1.4893	1.4893
1.75			1.7196	1.7238	1.7238
2.0			1.9454	1.9475	1.9475
2.5			2.3532	2.3541	2.3541
3.0	2.2662	2.4575	2.7000	2.7005	2.7005
4.0	2.9289	3.1137	3.2246	3.2248	3.2248
5.0	3.3625	3.5098	3.5749	3.5750	3.5750
7.5	3.9273	4.0095	4.0361	4.0362	4.0362
10.0	4.1716	4.2209	4.2357	4.2357	4.2357
15.0	4.3646	4.3882	4.3947	4.3947	4.3947
20.0	4.4364	4.4516	4.4553	4.4553	4.4553
40.0	4.5076	4.5120	4.5129	4.5129	4.5129
INF	4.5324	4.5324	4.5324	4.5324	4.5324

TABLE 2: Thickness Correction Factor (after ref. 1)

t/s	CF_t
0.4	0.9995
0.5	0.9974
0.5555	0.9948
0.6250	0.9898
0.7143	0.9798
0.8333	0.9600
1.0	0.9214
1.1111	0.8907
1.25	0.8490
1.4286	0.7938
1.6666	0.7225
2.0	0.6336

Table 3
(after ref. 3)

Approximate Resistivity	Set Current for (mA)
0.012	100
0.008 - 0.6	10
0.4 - 60	1
40 - 1200	0.1