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Contact Resistance Measurements in GaAs MESFET's and MODFET's by the Magneto-TLM Technique

David C. Look

Wright State University - Main Campus, david.look@wright.edu

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Contact Resistance Measurements in GaAs MESFET's and MODFET's by the Magneto – TLM Technique

D. C. Look

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Table I. Summary of germanium etching results

<table>
<thead>
<tr>
<th>Etch</th>
<th>Etch rate (µm/min)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>30:1:1</td>
<td>0.4</td>
<td>Hillocks</td>
</tr>
<tr>
<td>HNO₃:CH₂COOH:HF</td>
<td></td>
<td>10 min</td>
</tr>
<tr>
<td>20:1:1</td>
<td>1.1</td>
<td>Hillocks, scratches</td>
</tr>
<tr>
<td>HNO₃:CH₂COOH:HF</td>
<td></td>
<td>10 min</td>
</tr>
<tr>
<td>10:1:1</td>
<td>3.4</td>
<td>Rough surface</td>
</tr>
<tr>
<td>HNO₃:CH₂COOH:HF</td>
<td></td>
<td>10 min</td>
</tr>
<tr>
<td>18:8:5</td>
<td>13</td>
<td>Polishing, few ripples, best morphology</td>
</tr>
<tr>
<td>HNO₃:CH₂COOH:HF</td>
<td></td>
<td>3 min</td>
</tr>
<tr>
<td>18:8:5</td>
<td>11</td>
<td>Hillocks</td>
</tr>
<tr>
<td>HNO₃:CH₂COOH:HF</td>
<td></td>
<td>2 min</td>
</tr>
<tr>
<td>5:3:3 (CP-4A)</td>
<td>25</td>
<td>Hillocks</td>
</tr>
<tr>
<td>HNO₃:CH₂COOH:HF</td>
<td></td>
<td>5 min</td>
</tr>
<tr>
<td>5:3:3 (CP-4A)</td>
<td>26</td>
<td>Hillocks</td>
</tr>
<tr>
<td>HNO₃:CH₂COOH:HF</td>
<td></td>
<td>30s</td>
</tr>
<tr>
<td>10:1:1</td>
<td>0.44</td>
<td>Hillocks, scratches</td>
</tr>
<tr>
<td>H₂SO₄:HNO₃:HF</td>
<td></td>
<td>5 min</td>
</tr>
<tr>
<td>10:1:1</td>
<td>1.2</td>
<td>Hillocks, scratches</td>
</tr>
<tr>
<td>H₂SO₄:HNO₃:HF</td>
<td></td>
<td>10 min</td>
</tr>
<tr>
<td>1:1:1</td>
<td>0.33</td>
<td>Scratches</td>
</tr>
<tr>
<td>H₂O₂:HF:H₂O</td>
<td></td>
<td>60 min</td>
</tr>
<tr>
<td>1:1:4</td>
<td>1.7</td>
<td>Scratches</td>
</tr>
<tr>
<td>H₂O₂:HF:H₂O</td>
<td></td>
<td>5 min</td>
</tr>
<tr>
<td>10:1:2 (Caro’s etch)</td>
<td>0.01</td>
<td>Very slow, hillocks</td>
</tr>
<tr>
<td>H₂SO₄:H₂O₂:H₂O</td>
<td></td>
<td>30 min</td>
</tr>
</tbody>
</table>

HNO₃:CH₂COOH:HF etches with a high HF content were not used since they have been found to leave brown stains of insoluble GeO₃. Etches with lower HF concentrations were slower and bubbled less. These solutions still required agitation, and left ripples on the treated surfaces.

Other etch formulations were investigated in this study. Caro’s etch (H₂SO₄:H₂O₂:H₂O) used in a 10:2:1 formulation by volume, was found to be nonpolishing and slow. The etch process was limited by the dissolution of GeO₂ in water (5), and was found to remove only 0.4 µm after 30 min. H₂O₂:HF:H₂O (Superoxol etchant) solutions are faster, but nonpolishing. This etch system has been investigated previously and found (6) to leave hillocks and pits on the surface. They seem to be limited by the Ge oxidation kinetics and reaction product removal, even in very dilute formulations (such as 1:1:20 by volume) (7).

A fourth wet chemical system employed was H₂SO₄:HNO₃:HF. This etch is faster than Caro’s etch due to the addition of the complexing agent HF. This etch was also found to be nonpolishing and left hillocks on the treated surface, in spite of the high viscosity of H₂SO₄.

Summary

The chemical polishing of Ge substrates for subsequent epitaxy has been investigated. Various chemical etches for germanium have been studied, and the results summarized in Table I. It is found that only solutions from the HNO₃:CH₂COOH:HF family are polishing, with best results obtained from a 2-3 min treatment in an 18:8:5 parts by volume formulation.

Acknowledgments

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REFERENCES

Parameters deduced from this model include \( r_s \), the sheet resistance of the bulk material between the contacts, and \( R_c \), which is the sheet resistance of the material under the contacts. It is clear that we cannot determine \( \rho_c \) without assuming that \( R_c = r_s \) and there is no a priori way of making this claim without a supplementary measurement. One such supplementary measurement involves the so-called "end resistance," which is determined by means of a third contact (3). Another way to get information on \( R_c \) is to use a magnetic field in conjunction with the usual TLM measurements. This recently-introduced technique (4), called the magneto-TLM (MTLM), determines the mobility \( \mu \) of the material under the contact, as well as the mobility \( \mu \) and sheet carrier concentration \( n_s \) of the bulk material. If \( \rho_c \neq \mu_s \), then it can be safely assumed that \( R_c = r_s \) and \( \rho_c \) can be determined. If \( \rho_c = \mu_s \), still it may be possible to estimate \( R_c \) and thus \( \rho_c \).

Although the usual TLM and MTLM methods work well for single-layer devices, such as GaAs metal-semiconductor field-effect transistors (MESFET's), they are not applicable to two-layer devices, such as AlGaAs/GaAs modulation-doped FET's (MODFET's). In a separate paper, we have formulated a two-layer MTLM model (6), and will apply the results here. It is shown that erroneous conclusions can be drawn from the one-layer model.

**Summary of Theoretical Models**

Consider the commonly-used test pattern shown in Fig. 1a. The resistance between any two ohmic pads of width \( w \) and separation \( l \) will be given by

\[
R = 2R_c + \frac{r_s}{w} \tag{1}
\]

and thus a plot of \( R \) vs. \( l \) will have a slope \( r_s/w \), and a y-axis intercept, \( 2R_c \). If the contacts are modeled as transmission lines, and are "electrically long" (\( kl \gg 2 \)), then

\[
R_c = \frac{R_c}{\omega k} \sqrt{\frac{R_c \rho_s}{w}} \tag{2}
\]

where \( R_c \) and \( \rho_s \) were defined earlier, and \( k = \sqrt{R_c \rho_s} \), the inverse "transfer length." Unless \( R_c \) is known or can be assumed equal to \( r_s \), \( \rho_s \) cannot be determined. For example, if there is appreciable contact diffusion, as illustrated in Fig. 1c, then it is doubtful that \( R_c = r_s \).

In the MTLM, a perpendicular magnetic field is applied, and

\[
r_s = r_s (1 + \mu_s B^2) \tag{3a}
\]

\[
R_c = R_c (1 + \mu_s B^2) \tag{3b}
\]

where \( \mu \) is the bulk mobility and \( \mu_s \) is the mobility of the material under the contact. The validity of Eq. [3a] and [3b] is discussed in Ref. (6), but suffice it to say that for degenerate electrons, the case for most MESFET's and MODFET's, they hold for arbitrary \( B \) (ignoring quantum effects). It can also be argued that \( \rho_c \) is nearly independent of \( B \). Thus, the one-layer MTLM gives

\[
R = 2R_c (B) + \frac{r_s (B)}{w} \tag{4}
\]

\[
= 2R_c (1 + \mu_s B^2) + r_s (1 + \mu_s B^2) \frac{l}{w} \tag{5}
\]

where \( R_c = \sqrt{R_c \rho_s} \). It is clear that plots of \( R \) vs. \( B^2 \) and \( r_s \) vs. \( B^2 \), will give \( \mu_s \) and \( \rho_s \) respectively. Since \( r_s = 1/\rho_s \mu_s \), we can also determine \( n_s \), the bulk sheet carrier concentration. Thus, a separate Hall-effect measurement is not necessary.

For two-layer materials such as the MODFET structures shown in Fig. 1d, le, and 2, neither Eq. [1] nor Eq. [4] is applicable, in general. However, it is possible to solve the distributed-resistance circuit of Fig. 2, in closed form, if \( \rho_1 \gg \rho_2 \). We may note that Fig. 2 represents a much different two-layer circuit than the one solved recently in Ref. (7), since, in that work, the region under the contacts was not considered in detail.

The solution for the circuit of Fig. 2, if \( kl_1 \) and \( kl_2 \), is

\[
R = 2R_c + r_s l \frac{1}{w} \tag{6a}
\]

\[
= 2R_c (1 + \mu_s B^2) + r_s (1 + \mu_s B^2) \frac{l}{w} \tag{6b}
\]

where the \( C_i \) 's are "correction" factors due to the second layer

\[
C_1 = 1 + \frac{R_1}{R_2} \tag{6c}
\]

\[
C_2 = \left( \frac{k_2 \rho_2}{k_1 \rho_1} \right) \left( \frac{1}{1 + \frac{r_s}{k_1 \rho_1}} \right) \tag{6d}
\]

where \( k_1 = \sqrt{R_c \rho_s} \), \( k_2 = \sqrt{R_c \rho_s} \), \( k = \sqrt{r_s \rho_2} \), \( r_s \rho_2 \), and \( F(k) = \sinh (k l) / (1 + \cosh (k l)) \). Note that for \( k l < 1 \), \( F(kl) \sim k l / 2 \), while for \( k l > 4 \), \( F(kl) = 1 \). Thus, the usual plot of \( R \) vs. \( l \) will not be linear for the two-layer case unless \( l \approx 4k l^{-1} \), for all \( l \). For our sample, \( k l \approx 4 \) when \( l \approx 2.5 \mu m \), which includes three of the four \( l \) values in the TLM pattern. Note also that Eq. [5] reduces directly to Eq. [1] when \( r_s \rightarrow \infty \), whereas it might have been expected that the contact-layer parameters should enter, due to the possibility of current mixing still being able to occur in the contacts.
However, the theory does not allow this possibility, because of the original assumption $P_{c2} \gg P_{c1}$, which was necessary for a closed-form solution of the differential equations. If $P_{c2} \gg P_{c1}$, then current entering contact-layer 1 from bulk-layer 1 will not mix into contact-layer 2, but will flow directly into the contact metal. Fortunately, literature values (1, 7), suggest that $P_{c2} = 10^{-6} \Omega \cdot cm^2$, and $P_{c1} = 10^{-4} \Omega \cdot cm^2$, so that $P_{c2} >> P_{c1}$, as required.

The two-layer MTLM is simply Eq. [5] along with the magnetoresistance expressions

$$R = R_{0} = r_{0} = (1 + \mu_{c1}^{2}B_{c1}^{2})/\mu_{c1}$$  \hspace{1cm} [7a]$$

$$R_{i} = R_{0i} = r_{0i} = (1 + \mu_{ci}^{2}B_{ci}^{2})/\mu_{ci}$$  \hspace{1cm} [7b]$$

where $i = 1$ or 2, for the two layers. We then end up with four bulk parameters, $n_{sl1}, \mu_{l1}, n_{s2}$, and $\mu_{l2}$, and six contact parameters, $n_{sc1}, \mu_{c1}, n_{sc2}, \mu_{c2}, P_{c1}$, and $P_{c2}$.

Results and Discussion

In Fig. 3 we show the magnetic field dependence of the resistance vs. contact spacing for a GaAs MESFET with Au/Ge/Ni contacts, at 296 K. All R vs. l data were fitted by the linear least squares method, and the region near the origin is expanded to show the variation of R with B. Data for B = 4.5 and 13.5 kG were also taken, but are not shown in Fig. 3, for clarity. Note that Eq. [4] predicts that, if $\mu_{c1}^{2}B_{c1}^{2} \ll 1$, then the R vs. l curves should merge at B = $-\mu_{c1}^{2}R_{01}^{2}/\mu_{c1}$, and indeed, this is the case. In Fig. 4 we have plotted R vs. B for the MESFET, curves (a) and (a'), respectively. From these straight-line plots, we get $\mu_{c1}$ and $\mu_{c2}$, as shown in Table I along with other calculated results. Here it is seen that $\mu_{c1} = \mu_{c2}$, and thus we can be confident that $R_{c} = r_{c}$, and that $P_{c1} = P_{c2} = 6.3 \times 10^{-7} \Omega \cdot cm^2$, which agrees with Hall-effect measurements. Thus, the use of the magnetic field has given several, important, additional pieces of information, and has shown that the calculated $P_{c}$ is indeed correct.

At attempt was made to apply this same one-layer analysis to an Al_{0.15}Ga_{0.85}As/In_{0.15}Ga_{0.85}As MODFET structure, which had been previously investigated by several other techniques (8, 9). If we simply draw straight lines through the raw R vs. l data, and then plot $r_{c}$ and $R_{c2}^{2}$ vs. $B_{c2}^{2}$, as described above, the results are shown in curves (b) and (b'), respectively, of Fig. 4. It is obvious that the one-layer model fails badly, because the lines are not straight, especially $r_{c}$ vs. $B_{c2}^{2}$. Thus, we must apply a two-layer model.

The two-layer MTLM, consisting of Eqs. [5] and [7], was fitted with a least squares routine to the 77 K MODFET data of Fig. 5. The fit is excellent, whereas the one-layer fit is very poor. The 10 parameters, which typically were fitted in about 2s on a DEC8800 computer, are presented for two temperatures and various TLM models in Table II. Some of the parameters could not be determined with good precision. However, it is clear that $P_{c2} > P_{c1}$, which is necessary for the theory to be valid. The value of $P_{c1}$, about $1 \times 10^{-6} \Omega \cdot cm^2$, is typical for Au-Ge-Ni/n+-GaAs barriers. This MODFET had a 200 Å n+-GaAs cap layer for parasitic resistance reduction; the rest of the structure consisted of 350 Å n+-Al_{0.15}Ga_{0.85}As, 30 Å undoped Al_{0.15}Ga_{0.85}As, 200 Å p+-In_{0.15}Ga_{0.85}As, and 1 µm undoped GaAs (8). According to the results, contact layer 1 consists of $1 \times 10^{15} \ cm^{-2}$ electrons with a mobility of about 1200 cm$^{2}$/V-s; the latter, unfortunately, is very poorly determined. This carrier concentration is lower than that in the bulk, which could be due to a highly compensated region caused by Ga out-diffusion. Contact-layer 2, on the other hand, evidently consists of a large concentration ($n_{sc2} = 1 \times 10^{17} \ cm^{-2}$) of higher mobility electrons ($\mu_{c2} = 4000 \ cm^{2}/V-s$), and thus the use of the magnetic field has given several, important, additional pieces of information, and has shown that the calculated $P_{c}$ is indeed correct.
The bulk parameters given in Table II, $n_{b1}$, $n_{b2}$, $\mu_1$, and $\mu_2$ are all quite reasonable, and $n_{c1}$ and $\mu_{c1}$ are very consistent with Hall-effect measurements (8). The parallel conduction in the bulk AlGaAs, consisting of about $2 \times 10^{12}$ electrons/cm$^2$ with 1500 cm$^3$/V-s mobility, is quite large, but nonetheless expected from the 350Å of heavily doped material. Note that the one-layer MTLM gives mobilities which are too low, due to its neglect of parallel conduction. Also, the two-layer model shows that $n_c$ and $\mu_c$ are almost independent of temperature, which, incidently, is a significant advantage of the Al$_{10.15}$Ga$_{0.85}$As/In$_{0.15}$Ga$_{0.85}$As system over the more common Al$_{0.3}$Ga$_{0.7}$As/GaAs system (8). The reason is that the DX-center concentration is much lower for the former material so that low-temperature freeze-out is not as severe a problem.

In conclusion, we have shown that the addition of a magnetic field makes possible much more detailed studies of the bulk and contact regions, within the transmission-line model. The recently derived two-layer model works well for MODFET structures, and is especially valuable in conjunction with temperature-dependent investigations of the various parameters. However, some of the parameters in this model are not well determined for our sample, or need further interpretation, and thus much more work needs to be done.

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### Table II. Calculated bulk and contact electrical parameters for a MODFET

<table>
<thead>
<tr>
<th>Model</th>
<th>TJ(K)</th>
<th>$n_{b1}$ $10^{12}$ cm$^{-2}$</th>
<th>$n_{b2}$ $10^{12}$ cm$^{-2}$</th>
<th>$n_{c1}$ $10^{12}$ cm$^{-2}$</th>
<th>$n_{c2}$ $10^{12}$ cm$^{-2}$</th>
<th>$\mu_1$ cm$^2$/V-s</th>
<th>$\mu_2$ cm$^2$/V-s</th>
<th>$\mu_1$ $10^{12}$ cm$^2$/V-s</th>
<th>$\mu_2$ $10^{12}$ cm$^2$/V-s</th>
<th>$\rho_1$ $\Omega$ cm</th>
<th>$\rho_2$ $\Omega$ cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-layer*</td>
<td>300</td>
<td>1.2 ± 0.1</td>
<td>2.3 ± 0.4</td>
<td>0.72 ± 0.2</td>
<td>0.15 ± 0.05</td>
<td>11 = 2</td>
<td>0.7 ± 0.3</td>
<td>0.4 ± 0.1</td>
<td>0.12 ± 0.07</td>
<td>9 ± 4</td>
<td>1.0 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>77</td>
<td>1.3 ± 0.1</td>
<td>2.7 ± 0.5</td>
<td>2.73 ± 0.02</td>
<td>0.11 ± 0.02</td>
<td>8 ± 5</td>
<td>0.4 ± 0.3</td>
<td>0.6 ± 0.1</td>
<td>0.08 ± 0.03</td>
<td>7 ± 4</td>
<td>1.0 ± 0.5</td>
</tr>
<tr>
<td>One-layer*</td>
<td>300</td>
<td>1.8 ± 0.1</td>
<td>0.58 ± 0.02</td>
<td>1.1 ± 0.1</td>
<td>0.56 ± 0.01</td>
<td>1.2 ± 0.1</td>
<td>1.3 ± 0.1</td>
<td>0.97 ± 0.02</td>
<td>0.97 ± 0.02</td>
<td>2.4 ± 0.1</td>
<td>2.4 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>77</td>
<td>1.3 ± 0.1</td>
<td>2.3 ± 0.1</td>
<td>1.2 ± 0.1</td>
<td>0.58 ± 0.01</td>
<td>1.3 ± 0.1</td>
<td>1.3 ± 0.1</td>
<td>1.0 ± 0.1</td>
<td>1.0 ± 0.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Calculated from least squares fit to Eq. [5] and [7].
*Calculated from fit to Eq. [4] at low B. Assumption that $R_{b1} = R_{c1}$

---

Fig. 5. Resistance vs. contact spacing for MODFET material at 77 K. The solid line is a two-layer fit, using Eq. [5] and [7], and the dashed line is a one-layer fit, using Eq. [4].

Fig. 6. Bulk 2DEG mobility ($\mu_2$) and contact 2DEG mobility ($\mu_{c1}$) vs. temperature.
Trench Etches in Silicon with Controllable Sidewall Angles

Robert N. Carlile, Victor C. Liang, Olgiierd A. Palusinski, and Mitfkal M. Smadi

Department of Electrical and Computer Engineering, University of Arizona, Tucson, Arizona 85721

ABSTRACT

This paper describes the role of the temperature of the silicon wafer in controlling a deep trench etch sidewall angle and also the etch rate. In addition, we discuss the role of pressure in controlling etch rate and selectivity. This work was performed in a Tegal 1500 Test Bench. The temperature of the wafer could be held fixed as a function of time at any temperature between 20° and 200°C. Our chemistry is chloriform, CHCl₃ with O₂ and N₂ as additives. We have found that the sidewall angle of the trench (the angle that the sidewall makes with a normal to the wafer surface) could be varied continuously from about 32° at 40°C to 7° at 190°C. The sidewalls are typically planar and relatively smooth. The bottom of the trench becomes increasingly planar as sidewall angle decreases. In order for the above processes to occur, one must be able to control etch rate by 1800 Å/min as temperature of the wafer is varied over the same range. Finally, we will show that etch rate is a sensitive function of total gas pressure. By changing the total gas pressure from 300 to 1.2 torr, the etch rate will increase from 3000 to 8000 Å/min. The selectivity at the latter pressure exceeds 15.

We will emphasize the importance of controlling the wafer temperature. For example, we will show that trench sidewall angle is a sensitive function of wafer temperature. To a lesser extent, etch rate and selectivity are also affected by this parameter. For example, the sidewall angle can be varied from 32° to 7° by changing the wafer temperature from 40° to 190°C, respectively. Etch rate can be increased by 1800 Å/min as temperature of the wafer is varied over the same range. Finally, we will show that etch rate is a sensitive function of total gas pressure. By changing the total gas pressure from 300 to 1.2 torr, the etch rate will increase from 3000 to 8000 Å/min. The selectivity at the latter pressure exceeds 15.

In the next section, we define trench parameters. In the following sections we discuss: equipment used; work we have done in computer simulating our trench etches, and physical mechanisms the simulation suggests; a quantitative study of the temperature dependence of sidewall angle; and, the parameters which affect etch rate and selectivity. The final section is a summary and discussion of the paper.

Trench profile.—A sketch of the trench profile that we wish to achieve is shown in Fig. 1; it is characterized by a width a, depth h, and sidewall angle θ, measured with respect to the normal to the wafer surface. It is highly desirable that these three parameters should remain independently controllable. For the process that we have developed, we will show that this is the case.

For our process, the width at the top of the etch, a, is determined by and is nearly identical with the width of the mask line. This parameter remains fixed during the etch time. As we have stated above, the sidewall angle θ is an extremely sensitive function of the wafer temperature. The etch depth is sensitive to the total gas pressure and, of course, the etch time. It is a weak function of wafer temperature.

A scanning electron micrograph (SEM) of a trench which looks similar to the sketch in Fig. 1 is shown in Fig. 2a. Notice that the sidewalls and trench bottom are planar, and that these surfaces are relatively smooth.