Chapter - 3

Influence of Ni layer thickness on the contact resistance, magnetic properties and surface morphology

3.1 Introduction

Recipes based on AuGe/Ni/Au layers have been extensively used for fabricating Ohmic contacts to GaAs [1-3], GaAs/AlGaAs and other heterostructures [4-9]. However, there are many unresolved issues, including those that arise in the context of magnetic field sensor fabrication using the multilayers. These contacts are usually based on the preparation of a metallization structure of evaporated eutectic alloy film of AuGe (88:12 wt%) followed by a rapid-thermal anneal to a temperature of ~400°C. The use of eutectic composition of the AuGe alloy results in low contact resistance, due to enhanced diffusion of Ge into GaAs when the AuGe layer melts, causes a reduction in the width of the depletion layer and forms a tunneling contact. [10-13]. Although this contact has excellent reproducibility, it, however, suffers from poor surface morphology [14-16] as the AuGe alloy is prone to balling-up as it melts (m.p~360°C). The addition of a Ni layer and a thick Au over-layer is found to reduce, to some extent, the surface roughness during alloying [1, 14, 17, 18]. Several studies have shown that, apart from the diffusion of various elemental components into GaAs, significant changes occur in the metal film structure that could potentially influence electrical contact formation. For example, TEM studies have shown the presence of binary and ternary compounds, Ni$_3$Ge, Ni$_2$GeAs and Au-Ga alloys [10, 11, 19-21] in metallization structures cooled down from anneal temperature of 400-430°C. A correlation is reported between the presence of Ni$_2$GeAs (interspersed with Au-Ga on GaAs surface) and low contact resistance [11, 19].

Thick Ni layers are beneficial in improving morphology, [22, 23] which in turn influences contact area. The increasing of Ni layer thickness may have other undesirable
consequences: a) un-reacted Ni may make the structure ferromagnetic b) formation of compounds with Ni and Ge may deplete Ge and hence influence contact resistance. In the case of magnetic field sensor fabrication and application, the presence of ferromagnetic material, e.g. Ni, in the proximity of the sensor active area can, potentially, distort the measured field. Thus, reproducible, reliable Ohmic contacts to the 2DEG, that have very low contact resistances, smooth surface, good thermal stability and, for sensor applications, no magnetism, are essential. However, to our knowledge, no systematic studies have been reported on the magnetic properties and its dependence on processing conditions.

In this chapter we report the following studies

1. The possibility of using alternate structures without the ferromagnetic Ni, namely, AuGe/Au, AuGe/Ti/Au and AuGe/Cr/Au. A comparative study of the contact resistance, surface roughness and surface composition in this metallization layers AuGe/Au, AuGe/Ti/Au, AuGe/Cr/Au and AuGe/Ni/Au, after annealing treatments are carried out.

2. AuGe/Ni/Au metallization gives the lowest contact resistance. We report studies undertaken on the dependence of magnetization hysteresis loops, surface roughness and the contact resistance of alloyed AuGe/Ni/Au contacts on the following process parameters: Ni layer thickness (for a fixed AuGe layer thickness of \( \sim 100 \text{nm} \)), anneal temperature \( (T_A) \) and anneal duration \( (t_A) \) of post deposition anneal.

3. Similar studies were undertaken on samples with three different AuGe layer thicknesses, after indication emerged that the Ni/AuGe thickness ratio was important in determining the contact characteristics including magnetization.

### 3.2 Effect of Ti, Cr and Ni interlayer on AuGe/TM/Au Ohmic contacts

Ni layer deposited on AuGe is known to reduce roughness greatly and improve contact resistance [11, 12, 17, 18]. However, the suitability of Ni for fabrication of Hall magnetic sensors needs to be examined in detail, because of its ferromagnetic nature. Cr and Ti are also suitable as interlayer metal. They behave similarly to Ni in the Ohmic contact formation, though no systematic information is available. We have made a comparative
study of the post-anneal contact resistance, surface roughness and other effects in the metallization without any interlayer and with Ti, Cr and Ni as interlayer viz, AuGe/Au, AuGe/Ti/Au, AuGe/Cr/Au and AuGe/Ni/Au [24].

The contact resistance of the alloyed contacts is estimated by micro fabricating a pattern suitable for transmission line or transfer length model (TLM) by i-line lithography and lift-off as explained in chapter 2 [25, 26]. Prior to the deposition of metallization layers, the substrates were sputter cleaned in O\textsubscript{2} plasma. A metallization layer structure such as AuGe (88:12wt %) -100nm/TM -30nm/Au -200nm, (TM = Ti, Cr, Ni or none) was deposited on the GaAs/AlGaAs substrate (table 3.2.1).

<table>
<thead>
<tr>
<th>Table 3.2.1 GaAs/AlGaAs wafer and Ohmic contact metallization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au (200nm)</td>
</tr>
<tr>
<td>________________________________________________________________________________________________</td>
</tr>
<tr>
<td>TM(30nm), (TM=Ti, Cr, Ni or none) AuGe (100nm)</td>
</tr>
<tr>
<td>n\textsuperscript{+} (Si 1.5 x 10\textsuperscript{18}) GaAs</td>
</tr>
<tr>
<td>n\textsuperscript{+} (Si 1.5 x 10\textsuperscript{18}) Al\textsubscript{0.3}GaAs\textsubscript{0.7}</td>
</tr>
<tr>
<td>Intrinsic AlGaAs</td>
</tr>
<tr>
<td>Intrinsic GaAs</td>
</tr>
<tr>
<td>SI GaAs Substrate</td>
</tr>
</tbody>
</table>

The substrates with the TLM patterns were annealed between 350°C to 450°C in N\textsubscript{2} ambient for different durations using RTA (chapter 2) at a heating rate of 250°C /min. I-V characteristics are measured for estimation of contact resistance (R\textsubscript{c}). The surfaces of the annealed contact pads are examined for morphology by scanning electron microscopy (SEM), energy dispersive x-ray analysis (EDX) and atomic force microscopy (AFM).

### 3.2.1 Electrical characteristics

The contact resistance, R\textsubscript{TC}, as a function of anneal temperature for (a) AuGe/Au, (b) AuGe/Ti/Au, (c) AuGe/Cr/Au and (d) AuGe/Ni/Au is shown in figure 3.2.1.

1. The contacts show Ohmic behavior for anneal temperatures ≥350°C. The contact resistance decreases as the interlayer is changed from no interlayer to Ti to Cr to Ni.
2. The lowest, or optimum, contact resistance is observed for anneal temperatures \(\sim 400^\circ C\) for AuGe/Au, and with Cr, Ti, Ni interlayer. Among these, the lowest contact resistance of 0.07\(\pm\)0.005 \(\Omega\)-mm is observed for AuGe/Ni /Au for 90 second anneal for the thickness mentioned in table 3.2.2.

3. Increase of anneal temperature results in increase of the contact resistance.

![Figure 3.2.1](image1.png)

**Figure 3.2.1** Contact resistances as a function of anneal temperature for AuGe/Au, AuGe/Ti/Au, AuGe/Cr/Au and AuGe/Ni/Au. The lines are a guide to the eye.

![Figure 3.2.2](image2.png)

**Figure 3.2.2** Contact resistances as function of anneal durations for AuGe/Au, AuGe/Ti/Au, AuGe/Cr/Au and AuGe/Ni/Au.
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The dependence of the contact resistance of AuGe/TM/Au alloyed contacts on anneal durations is shown in figure 3.2.2. Contact resistance at the optimum anneal temperature and durations for various TM are listed in table 3.2.2

**Table 3.2.2** Optimum anneal temperatures and durations, optimum contact resistance and the surface roughness for AuGe/Au, AuGe/Ti/Au, AuGe/Cr/Au and AuGe/Ni/Au.

<table>
<thead>
<tr>
<th>Metallization</th>
<th>Optimum alloying temperature(°C)</th>
<th>Alloying time (s)</th>
<th>Contact resistance (Ω-mm)</th>
<th>Surface roughness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AuGe -100nm/Au-200nm</td>
<td>400</td>
<td>60</td>
<td>3.5</td>
<td>44 ± 4</td>
</tr>
<tr>
<td>AuGe-100nm/Ti-30nm/Au-200nm</td>
<td>400</td>
<td>90</td>
<td>0.38</td>
<td>40 ± 3</td>
</tr>
<tr>
<td>AuGe-100nm/Cr-30nm/Au-200nm</td>
<td>400</td>
<td>90</td>
<td>0.13</td>
<td>26 ± 3</td>
</tr>
<tr>
<td>AuGe-100nm/Ni-30nm/Au-200nm</td>
<td>400</td>
<td>90</td>
<td>0.07±0.005</td>
<td>21 ± 2</td>
</tr>
</tbody>
</table>

**3.2.2 Surface morphology**

The as-deposited film morphology is shown in the figure 3.2.3. These are SEM and AFM micrographs of a sample with the metallization structure AuGe/Cr/Au. Prior to annealing, the film is uniform with surface roughness ∼2nm.

The surface roughness increases by a factor of 10-20 after anneals at 400°C, for durations that gave the lowest contact resistance.

The rms roughnesses are in the range of 40nm-20nm for AuGe/Au and AuGe/TM/Au as measured by AFM. The SEM micrographs of the sample surface (figure 3.2.4) clearly indicate that the sample roughness decreases systematically as the interlayer is varied from no interlayer Ti to Cr to Ni.

**Figure 3.2.3** SEM & AFM micrographs of the surface of as-deposited un-annealed sample.
When interlayer is not used, the alloy film tends to ball up and formation of blisters/bubbles is observed on the film structure probably due to Ga from the GaAs cap layer, migrating to the surface (figure 3.2.4). The SEM data of the bright portion of the micrographs indicate that these are Au agglomerations and profiler data show that these are 10-20 \( \mu \text{m} \) across and 0.5-1 \( \mu \text{m} \) high. This roughening could limit the close approach
of the sensor active areas to the surface under examination. For samples with Ni interlayer, coverage by Au is nearly complete, though roughness can still be detected at high magnification.

It is observed from these results that AuGe/Ni/Au gives the lowest contact resistance with smooth surface. However as-deposited Ni is magnetic, and the magnetization of the structure after alloying is of interest, in the context of Hall magnetic field sensor fabrication using GaAs/AlGaAs multilayer. Hence a study of influence of Ni layer and its thickness on magnetic properties, contact resistance and surface roughness is of relevance in the magnetic field sensor fabrication and application.

3.3 Influence of Nickel layer thickness on contact resistance, magnetic properties and surface roughness.

The magnetic hysteresis loops, contact resistance and surface morphology are evaluated as functions of Ni layer thickness and anneal temperature. The contact resistance of the alloyed contacts is estimated using TLM [25]. The preparation of the metallization structure is as explained in chapter 2. AuGe (88:12) -100nm/Ni -x nm/Au -200nm, where \( x = 10, 25, 30, 50, 75, 100 \) nm, deposited on the GaAs/AlGaAs wafer and rapid thermal annealed between 350-450°C (table 3.3.1). I-V characteristics at various pads are measured using a wafer-prober and device analyzer.

<table>
<thead>
<tr>
<th>Table 3.3.1 Ohmic contact metallization structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au (200nm)</td>
</tr>
<tr>
<td>Ni (10,25,30,50,75,100nm)</td>
</tr>
<tr>
<td>AuGe (100nm)</td>
</tr>
<tr>
<td>GaAs/AlGaAs Multilayer wafer with n⁺-GaAs cap layer</td>
</tr>
</tbody>
</table>

3.3.1 Electrical characteristics

Figure 3.3.1 summarizes the contact resistance, \( R_{TC} \) as a function of anneal temperature for varying Ni layer thicknesses with optimized anneal durations.
1) The contacts with Ni layer thickness, 100 nm, show a non-linear, large resistance (∼4 MΩ) contacts for long duration anneals (∼10 min.) as shown in figure 3.3.2. Shorter anneals (<4min) at all temperatures upto 430°C resulted in a diode-like characteristic similar to those obtained for samples with smaller Ni layer thickness annealed at low temperature (figure 3.3.3).

Figure 3.3.1 Contact resistances as a function of anneal temperature for varying Ni layer thicknesses on linear and log scale

Figure 3.3.2 I-V curve for AuGe-100nm/Ni-100nm/Au-200nm for anneal duration of 10 minutes
2) The contacts with Nickel layer thicknesses 50nm and 75nm show diode-like behavior when annealed at temperatures below 400°C and Ohmic behavior for anneal temperatures above 400°C.

3) The contacts with Ni layer thickness 25nm and 10nm show Ohmic behavior for anneal temperatures above 350°C.

4) I-V curves for AuGe/Ni(x nm)/Au with (x=10, 25, 50, 75nm) optimized for low contact resistance are shown in the figure 3.3.4.

5) The nature of the contacts for various Ni-layer thicknesses and anneal temperatures are summarized in fig. 3.3.5.
Annealing at 430°C is found to increase the contact resistance marginally for Ni layer thicknesses 10, 25, 50 and 75nm. The lowest, or optimum, contact resistance is observed for anneal temperatures $\sim 400°C$ for each of the Ni layer thicknesses 10, 25, 50, 75nm (Table 3.3.2). The dependence of the contact resistance of AuGe/Ni/Au alloyed contacts on anneal durations with various Ni layer thicknesses is shown in figure 3.3.6. These results indicate that if the Ni-layer thickness is increased, a larger anneal time is required to optimize the contact resistance.

Figure 3.3.6 Contact resistances as function of anneal time for different Ni layer thicknesses on linear and log scale.
Table 3.3.2 Optimum anneal temperatures and durations, contact resistance, surface roughness and the magnetic-to-non magnetic transition temperature, for various Ni layer thicknesses

<table>
<thead>
<tr>
<th>Nickel layer thickness (nm)</th>
<th>Optimum anneal temperature (°C)</th>
<th>Optimum anneal duration (s)</th>
<th>Contact resistance (Ω-mm)</th>
<th>Surface Roughness (nm)</th>
<th>Anneal temperature for conversion of magnetic phase to non-magnetic phase (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>400</td>
<td>60</td>
<td>0.15</td>
<td>25 ± 4</td>
<td>100- 200</td>
</tr>
<tr>
<td>25</td>
<td>400</td>
<td>60</td>
<td>0.05±0.01</td>
<td>21 ± 3</td>
<td>200- 250</td>
</tr>
<tr>
<td>30</td>
<td>400</td>
<td>90</td>
<td>0.07±0.005</td>
<td>20± 2</td>
<td>200- 250</td>
</tr>
<tr>
<td>50</td>
<td>400</td>
<td>150</td>
<td>0.90</td>
<td>11± 1</td>
<td>250- 300</td>
</tr>
<tr>
<td>75</td>
<td>400</td>
<td>180</td>
<td>1.40</td>
<td>7.5 ± 0.5</td>
<td>350- 400</td>
</tr>
<tr>
<td>100</td>
<td>400</td>
<td>480</td>
<td>Non linear</td>
<td>3 ± 0.3</td>
<td>400- 430</td>
</tr>
</tbody>
</table>

Dependence of $R_{TC}$ on Ni layer thickness, optimized with respect to anneal temperature and time, is shown in figure 3.3.7. Among these, the lowest contact resistance of 0.05±0.01 Ω-mm is observed for AuGe (88:12 wt %) /Ni /Au configuration with Ni layer thickness 25nm, for a 60 second anneal. The quoted error (table 3.3.2) is the r.m.s deviation over several separate deposition runs. The best contacts are reproducible.

![Contact resistances at the optimized anneal temperature and time vs. Ni layer thickness.](image)

**Figure 3.3.7** Contact resistances at the optimized anneal temperature and time vs. Ni layer thickness.
The optimum Ni layer thickness for a given AuGe layer thickness, in this case 25-30 nm Ni-layer thickness for a 100nm Au-Ge layer thickness (figure 3.3.7), for obtaining the least contact resistance. Moreover under these conditions, the contact resistance variations with the process parameters, Ni layer thickness, anneal temperature and time corresponds to a reasonably shallow minimum which offers good process tolerance.

3.3.2 Magnetic properties

The magnetization hysteresis loops of the alloy structures were measured using a Vibrating Sample Magnetometer (VSM), with a magnetic moment resolution of $10^{-6}$ emu. The measurements were carried out in sweep mode to 5 KG with the magnetic field applied parallel to the film plane. Pieces of GaAs/AlGaAs wafer with area 4 mm$^2$, were metallized with the structure AuGe (100nm)/Ni($x$ nm)/Au (200nm), $x=10, 25, 50, 75, 100$. The pieces were rapid thermal annealed at 100$^\circ$C, 200$^\circ$C, 250$^\circ$C, 300$^\circ$C, 400$^\circ$C and 430$^\circ$C. They were then subjected to magnetic hysteresis loop measurements using VSM at room temperature. Background due to a sample of the same mass, but without the film structure, was subtracted and the resultant data was normalized by the Ni film mass (see chapter 2).

The magnetization hysteresis loops for AuGe (100nm)/Ni($x$ nm)/Au (200nm), $x=10, 25, 50, 75, 100$ and annealed at 100$^\circ$C, 200$^\circ$C, 250$^\circ$C, 300$^\circ$C, 400$^\circ$C and 430$^\circ$C are shown in figure 3.3.8. These data are typical of the magnetic behaviour of the Ni-containing contact metallization structures. The data show that, while hysteresis loops of the as-deposited film structure are ferromagnetic, the loops become progressively less magnetic after being subjected to anneal at increasing temperatures. Figure 3.3.9 shows the saturation magnetization (measured at an applied field of 5 kG) of samples with the metal film structure, as a function of the anneal temperature. The magnetization data are presented as a percentage of the magnetization of the as-deposited (un-annealed) sample as anneal temperature is increased. Remarkably, substantial decreases in magnetization occur even for anneal temperatures as low as 100$^\circ$C. The anneal temperature for which the structure becomes completely non-magnetic, increases with increasing Ni-layer thickness as shown in table 3.3.2.
Figure 3.3.8 Magnetization hysteresis loops for AuGe/Ni (10, 25, 50, 75, 100nm)/Au annealed at various anneal temperatures for 30s.
Figure 3.3.9 Anneal temperature dependence of saturation magnetization of alloyed structures of the form AuGe (100nm) /Ni=x nm/Au (200nm) on GaAs multi-layer, for x= 10 nm, 25 nm, 50 nm, 75 nm, 100 nm. Data for a structure AuGe (50nm)/Ni (25nm)/Au (200nm) and AuGe (150nm) /Ni (75nm)/Au (200nm) are also included. $M_{s0}$ is saturation magnetization of the as-deposited sample at 5kG.

Figure 3.3.10 Magnetic to non-magnetic transition temperature as a function of Ni layer thickness.
The structure becomes completely non-magnetic on annealing at or above a temperature which varies from 200°C to 430°C as the Ni layer thickness varies from 10nm to 100nm. The minimum anneal temperature required to complete the transformation to a non-magnetic phase is unknown, but lies in the range given in table 3.3.2 and figure 3.3.10. It is to be noted that under conditions normally used for obtaining Ohmic contacts, the structure is non-magnetic for a wide range of Ni layer thicknesses. All the samples with Ni-layer thickness ≤75nm become non-magnetic on annealing at a temperature of 400°C, a commonly used anneal temperature in alloyed Ohmic contact recipes (Table 3.3.2). The structure with 100nm-thick Ni-layer becomes non-magnetic on annealing at 430°C.

3.3.3 Surface morphology

The surfaces of the annealed contact pads are examined by scanning electron microscopy (SEM), energy dispersive x-ray analysis (EDAX) and atomic force microscopy (AFM). The roughness is computed using the root-mean-square height of the sample over an area of about 5µm×5µm of the Dynamic Force Microscopy (DFM) topography data. The data have been repeated at several pads of the TLM structure.

AFM images of the AuGe/Ni/Au structures on GaAs/AlGaAs wafer corresponding to different Ni layer thicknesses and annealed at 400°C for durations that gave the lowest contact resistance, are shown in figure 3.3.11. The r.m.s. surface roughness calculated are listed in table 3.3.2. They are in the range 24nm-6nm for Ni-layer thickness 10nm-100nm.
Figure 3.3.11 AFM micrographs (5µm x 5µm) of the surface of AuGe /Ni(x)/Au, x= 10 nm (a), 25 nm (b), 50 nm (c), 75 nm (d), 100 nm (e), annealed at 400°C for durations that gave the lowest contact resistance (Table 3.3.2).

Figure 3.3.12 Surface roughness as a function of Ni layer thickness
Figure 3.3.13 SEM micrographs of the surface of AuGe/Ni/Au, (a) as deposited (b) x = 10 nm, (c) 25 nm, (d) 50 nm (e) 75 nm and (f) 100 nm annealed at 400°C for durations that gave the lowest contact resistance (Table 3.3.2).
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The measured surface roughness as function of Ni layer thickness is shown in figure 3.3.12. Increasing the Ni layer thickness reduces roughness of annealed contacts, but also increases contact resistance. For the structures with the optimum contact resistance the surface roughness is ~20nm.

SEM micrographs of AuGe/Ni/Au as deposited, un-annealed sample and AuGe/Ni (10, 25, 50, 75, 100)/Au deposited samples and annealed at 400°C durations that gave low contact resistance (Table 3.3.2) are shown in figure 3.3.13. The metallization is smooth in the case of as deposited and AuGe/Ni-100nm/Au samples and EDAX analysis shows Au, Ga and As rich phases. SEM micrographs of the AuGe/Ni (10, 25, 50, 75)/Au deposited samples (figure 3.3.13) show agglomeration into Au-rich (bright) and Au poor (dark) regions.

EDAX analysis shows the bright regions are rich in Au and Ga and the dark regions are Ga and As. As the Ni layer thickness is increased, agglomerations on much smaller scale are seen in the ‘dark’ regions which structure eventually covers the entire surface for Ni-layer thickness >50nm.

3.3.4 Influence of Ni-to-AuGe layer thickness ratio

The data discussed in the previous section correspond to samples with a fixed AuGe layer thickness of 100nm. A few measurements were also performed on samples with other AuGe thicknesses- namely 50 nm and 150 nm. The motivation was to determine if the Ni-layer thickness to AuGe layer thickness ratio was influential in determining contact resistance (as suggested in some studies [27]), roughness and magnetic properties.

The magnetic hysteresis loops for AuGe (88:12wt%)-50nm/Ni-25nm/Au-200nm and AuGe-150nm/Ni-75nm/Au-200nm (viz. Ni to AuGe thickness ratio constant at 0.5) are shown in figure 3.3.14.
Further, as shown in Figure 3.3.15 the magnetic behaviour of the samples with structures AuGe (150nm)/Ni (75nm)/Au (200nm) and AuGe (100nm)/Ni (50nm)/Au (200nm), AuGe(50nm)/Ni(25nm)/Au(200nm) are virtually identical when the magnetization data, plotted against anneal temperatures, are normalized by the magnetization of as-deposited sample (figure. 3.3.15).

**Figure 3.3.14** Magnetization hysteresis loops for AuGe (50, 150)/Ni (25, 75)/Au (200nm) annealed at various anneal temperatures for durations ~1 minute.

Further, as shown in Figure 3.3.15 the magnetic behaviour of the samples with structures AuGe (150nm)/Ni (75nm)/Au (200nm) and AuGe (100nm)/Ni (50nm)/Au (200nm), AuGe(50nm)/Ni(25nm)/Au(200nm) are virtually identical when the magnetization data, plotted against anneal temperatures, are normalized by the magnetization of as-deposited sample (figure. 3.3.15).

**Figure 3.3.15** Anneal temperature dependence of saturation magnetization of alloyed structures of the form AuGe (50nm)/Ni (25nm)/Au (200nm), AuGe (100nm) /Ni (50nm)/Au (200nm) and AuGe (150nm)/Ni (75nm)/Au(200nm) on GaAs/AlGaAs multi layer.
Figure 3.3.16 and table 3.3.3 shows the contact resistance and surface roughness measurements with AuGe layer thicknesses of 50, 100, 150nm with different Ni/AuGe ratios. The surface roughness appears to depend on the Ni and AuGe layer thicknesses through their ratio.

![Graph showing contact resistance and surface roughness](image)

**Figure 3.3.16** Contact resistances and surface roughness of AuGe/Ni/Au contacts with various AuGe layer thicknesses and for Ni/AuGe film thickness ratios 0.25 and 0.5.

**Table 3.3.3** Anneal temperatures and durations optimized for the lowest contact resistance, the contact resistance and surface roughness, for various AuGe thicknesses and different Ni/AuGe ratio.

<table>
<thead>
<tr>
<th>AuGe thickness (y nm)</th>
<th>50</th>
<th>100</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni thickness (z nm)</td>
<td>12.5</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Ni/AuGe thickness ratio (z/y)</td>
<td>0.25</td>
<td>0.5</td>
<td>0.25</td>
</tr>
<tr>
<td>Optimum anneal temperature (°C)</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Optimum anneal time (s)</td>
<td>60</td>
<td>180</td>
<td>60</td>
</tr>
<tr>
<td>Contact resistance (Ω-mm)</td>
<td>0.90</td>
<td>2.95</td>
<td>0.05±0.01</td>
</tr>
<tr>
<td>Surface roughness (nm)</td>
<td>22±2</td>
<td>10.5±1</td>
<td>21±3</td>
</tr>
<tr>
<td>Anneal temperature for conversion of magnetic phase to non-magnetic phase (°C)</td>
<td>250-300</td>
<td>200-250</td>
<td>250-300</td>
</tr>
</tbody>
</table>

Contact resistances close to the optimum are obtained if the Ni to AuGe layer thickness ratio is about 0.25 or less (with the exception of sample with low AuGe thickness ~50nm). These results are consistent with previous suggestions on alloyed Ohmic contacts to AlGaAs/GaAs heterostructures [28]. Some published procedures [23]
for Ohmic contacts to GaAs use separate Au, Ge, Ni layers of the form Au (600nm)/Ni (50nm)/Ge (40nm)/Au (100nm). In order to correlate these results, we compute the ratio of the number of atoms per unit area of Ge and to Ni atom ratio per unit area.

For AuGe (100nm)/Ni (25nm)/Au (200nm), the ratio of the number of atoms per unit area of Ge and to Ni atom ratio per unit area at this Ni layer thickness (25nm), for the AuGe thickness of 100nm, comes to approximately 1.

\[
x = \frac{t_{\text{Ni}}}{t_{\text{AuGe}}} \frac{d_{\text{Ni}}}{d_{\text{AuGe}}} 1.0 \frac{M_{\text{Ge}}}{M_{\text{Ni}}} = \frac{25}{100} \frac{8.908}{19.3} \frac{1.0}{0.12} \frac{72.6}{58.70} = 1.18
\]

\( t_{\text{Ni}} \) and \( t_{\text{AuGe}} \) are the thickness of Ni (25nm) and AuGe (100nm), \( d_{\text{Ni}}, d_{\text{AuGe}} \) are the densities of Ni and AuGe, which are \( 8.908 \times 10^3 \) kg/m\(^3\) and \( 19.3 \times 10^3 \) kg/m\(^3\) respectively. \( M_{\text{Ni}}, M_{\text{Ge}} \) are the molecular weight of Ni and Ge, which are 58.7g/mol and 72.6 g/mol respectively.

Procedures utilizing separate Ge, Au and Ni layers [23] find optimum contact resistance formation around 1:1 for the Ge: Ni layer thickness ratio which corresponds to 1:2 for the atom areal density ratio.

\[
\text{At } \frac{t_{\text{Ni}}}{t_{\text{Ge}}} = 1, \quad \frac{\text{Ni}}{\text{Ge}} \text{ (atomic ratio)} = \frac{t_{\text{Ni}}}{t_{\text{Ge}}} \frac{d_{\text{Ni}}}{d_{\text{Ge}}} 1.0 \frac{M_{\text{Ge}}}{M_{\text{Ni}}} = 2
\]

**Discussions**

Process conditions used frequently in practice, viz., 400°C anneal for a minute, result in a non-magnetic contact structure with the contact resistance close to the optimum (\(~0.04 \ \Omega\text{-mm}\)). This also requires that the AuGe layer thickness should be larger than 50nm, and thickness ratio of Ni/AuGe less than 0.5, conditions that are usually met in practice (table 3.3.3). Total film thickness of \(~450\) nm approaches the maximum suitable for a lift-off patterning process for a typical photoresist thickness of 1 μm.

A significant result of the study is that under conditions normally used for obtaining Ohmic contacts with an AuGe/Ni/Au metallization structure, Ni is rendered non-magnetic after processing. The magnetization data of table 3.3.2 indicates that the samples with Ni layer thickness of \(~10\)nm-100nm are non-magnetic at room temperature, after the metal film structure is annealed at 430°C for x=100nm, and 400°C...
for x=10-75nm. These are the anneal temperatures most commonly used for Ohmic contact formation. Literature and measured microstructural data is discussed in chapter 5. It is apparent, from the magnetization data presented here, that the transformation of ferromagnetic Ni to a non-magnetic compound or alloy begins at temperatures as low as 100°C and probably room temperature in all samples. The contact resistance is still quite high at these temperatures as shown in figure 3.3.3.

The electrical contact formation, however, appears to begin at much higher temperatures than 100°C. Figure 3.3.5 is a summary of the nature of contacts for variation of Ni layer thicknesses and anneal temperature. In any case, experimental data clearly indicates that Ni layer is beneficial at low thickness, for Ohmic contact formation. Our contact resistance data on similar structures but without the Ni-layer are two orders of magnitude higher than (3.5Ω-mm) for structures with Ni-layers but of low (< 50nm) thicknesses (table 3.2.2). When small Ni-layer- AuGe (100nm)/Ni (10nm) thicknesses are used, the contact resistance increases marginally. This may due to a reduced contact area resulting from the considerable surface roughening coupled with non-conformal coverage of Ni layer.

Further measurements and discussions that provide insights into the contact mechanism are discussed in chapter 5.

3.4 Conclusions

1. Systematic studies of the variation of the contact resistance with Ni-layer thickness on a sample with Au-Ge layer thickness of 100nm indicate that the lowest contact resistance of (0.05±0.01 Ω-mm) is obtained at a Ni layer thickness of 25nm when annealed at 400°C.

2. At low Ni layer thickness (<25nm) slight increase in contact resistance is observed relative to the optimum, probably due to a decrease in contact area resulting from the surface roughening.

3. Measurements on samples with other AuGe layer thicknesses suggest that the contact resistances are comparable to this optimum value, if the Ni to AuGe layer thickness ratio is about 0.25 or less.
4. Increasing the Ni layer thickness reduces roughness of annealed contacts, but increases contact resistance.

5. Magnetization hysteresis studies on commonly used metallization of the form AuGe/Ni/Au on GaAs/AlGaAs multilayers indicate that all metallizations are non-magnetic at room temperature after annealing at 400°C (430°C for Ni layer thickness 100nm).

6. Conversion of Ni to non-magnetic phase begins for anneals at temperatures as low as 100°C and is completed at an anneal temperature that increases with Ni layer thickness.

7. The fraction of Ni remaining magnetic as function of anneal temperature is nearly identical for samples with structures AuGe (150 nm)/Ni (75 nm)/Au (200 nm), AuGe (100 nm)/Ni (50 nm)/Au (200 nm) and AuGe (50nm)/Ni (25nm)/Au (200nm).
References


