

NiGeAu Ohmic Contact in InGaP pHEMTs

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Abstract

NiGeAu ohmic contact as a function of alloying temperature on InGaP/InGaAs pHEMT structure was investigated. It was found that the optimum RTA condition is 460°C 60 sec for n+ contact resistance, whereas 420°C 30 sec for on-resistance. Electron microscope examinations of the cross-sectional samples annealed at these two conditions revealed three types of alloy grains. Chemical compositions of these grains were obtained by the nano-probe X-ray energy dispersive spectrum (EDS) analysis. A correlation between these alloy grains and the contact resistance and on-resistance was established.

INTRODUCTION

There has been great interest in replacing AlGaAs with InGaP material in GaAs based pHEMT device structures for the following reasons. First, there is good etch selectivity between GaAs and InGaP materials, which improves process yields and reduces die costs. Secondly, InGaP does not have DX centers as in the case of AlGaAs material, which will improve the RF swing at the open channel condition especially for the higher supply voltage operation. Thirdly, InGaP material lattice matched to GaAs breaks down at a higher electric field than the AlGaAs material normally used in AlGaAs/InGaAs pHEMTs, which will provide a higher off state breakdown and benefit the high voltage operation.

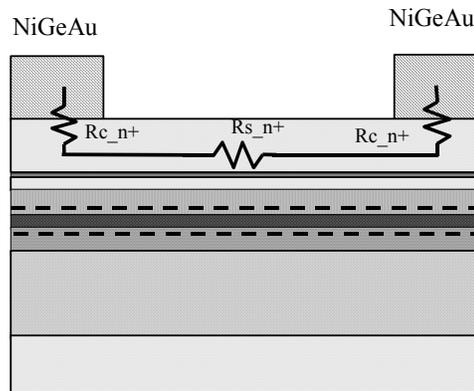
The quality of ohmic contact directly impact the RF swing and efficiency of the power amplifier. In the current CS1 AlGaAs/InGaAs pHEMT2 flow, hypoeutectic AuGe/Ni ohmic contact process is utilized [1]. For InGaP/InGaAs structure, due to the existence of In and P contents, a lower ohmic alloy temperature may be expected [2]. In this paper, we present the AuGe/Ni ohmic RTA process optimization on InGaP/InGaAs pHEMT structure. Microstructures of the ohmic grains were characterized by TEM and nano-probe X-ray energy dispersive spectrum (EDS) analysis. These grains are used to explain the observed contact resistance and on-resistance.

OHMIC EXPERIMENT

NiGeAu ohmic RTA experiment was performed on an InGaP/InGaAs pHEMT structure. This InGaP/InGaAs pHEMT has a double heterojunction structure with a lattice matched InGaP Schottky barrier layer on top of an undoped InGaAs channel, as illustrated in Fig. 1. At room temperature, the typical sheet charge and mobility of the structure is $2.0 \times 10^{12} \text{ cm}^{-2}$ and $6500 \text{ cm}^2/\text{Vs}$, respectively.

| |
|------------------------|
| GaAs Cap |
| InGaP Etch Stop |
| GaAs Recess |
| InGaP Schottky Barrier |
| Si- δ Doping |
| InGaP Spacer |
| InGaAs Channel |
| AlGaAs Spacer |
| Si- δ Doping |
| AlGaAs Barrier |
| Buffer Layer |
| GaAs Substrate |

Fig.1 Double heterojunction structure of the InGaP/InGaAs pHEMT.



(a)

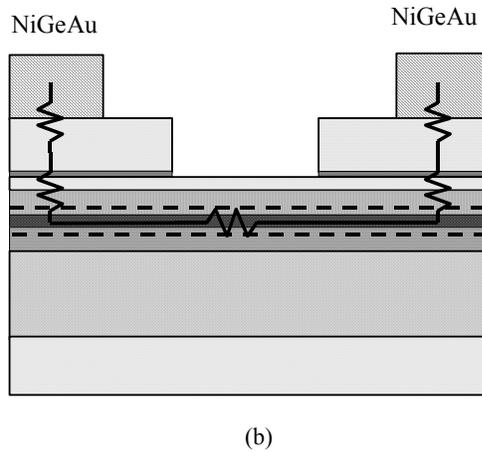


Fig. 2 TLM patterns for (a) n+ contact resistance (R_{c_n+}), and (b) on-resistance (R_{on}) measurements.

To evaluate the quality of ohmic contact and its contribution to the device, transmission line model (TLM) method was used to calculate the contact resistance. TLM pattern in Fig. 2(a) is used to measure the AuGe/Ni ohmic contact resistance to the n+ GaAs, R_{c_n+} . Whereas the structure in Fig. 2(b) can be used to measure the on-resistance of the FET, R_{on} , because n+ GaAs was etched away between the two contacts as in the real devices. Au/Ge/Ni (300 nm/20 nm/20 nm) ohmic metal stack was evaporated, and subsequently the wafers were annealed at 380°C to 460°C for a period of 30 to 90 seconds. Table I and II list the n+ contact resistance R_{c_n+} and on-resistance R_{on} under various ohmic RTA conditions for two sets of samples that were grown by two epi vendors. It can be seen from Table I and II that R_{c_n+} reaches a minimum at the

Table I. N+ contact resistance R_{c_n+} and on-resistance R_{on} on InGaP/InGaAs epi wafers from one vendor.

| Sample # | RTA Temp (°C) | RTA Time (sec) | R_{c_n+} (Ω -mm) | R_{on} (Ω -mm) |
|----------|---------------|----------------|-----------------------------|--------------------------|
| 69L | 380 | 60 | 0.70 | 4.14 |
| 62R | 380 | 90 | 0.56 | 3.38 |
| 71L | 420 | 30 | 0.46 | 2.78 |
| 69R | 420 | 60 | 0.47 | 3.13 |
| 73L | 420 | 90 | 0.45 | 3.03 |
| 71R | 420 | 120 | 0.41 | 3.20 |
| 67L | 460 | 30 | 0.24 | 3.60 |
| 73R | 460 | 60 | 0.22 | 3.63 |

Table II. N+ contact resistance R_{c_n+} and on-resistance R_{on} on InGaP/InGaAs epi wafers from another vendor.

| Sample # | RTA Temp (°C) | RTA Time (sec) | R_{c_n+} (Ω -mm) | R_{on} (Ω -mm) |
|----------|---------------|----------------|-----------------------------|--------------------------|
| 10L | 380 | 60 | 0.74 | 4.35 |
| 8L | 420 | 30 | 0.42 | 2.70 |
| 5L | 420 | 60 | 0.46 | 2.75 |
| 8R | 420 | 90 | 0.16 | 3.48 |
| 5R | 460 | 60 | 0.17 | 3.89 |

RTA condition of 460°C 60 sec, whereas R_{on} reaches a minimum at a lower RTA temperature of 420°C and a less RTA time of 30 sec. In addition, the difference in R_{on} at two RTA conditions is 1.19 Ω -mm on samples in the Table II, as large as 30%. This behavior, that R_{c_n+} and R_{on} have different optimal RTA condition, is characteristic of AuGe/Ni ohmic contact on the GaAs/InGaP/InGaAs structure. We have found this behavior on the InGaP/InGaAs pHEMT wafers consistently. Ohmic RTA experiment was also performed on the GaAs/AlGaAs/InGaAs pHEMT structure with the same GaAs n+ thickness. In comparison, the difference in R_{on} is within 5%, only 0.1 Ω -mm between 460°C 60 sec and 420°C 30 sec. Therefore, GaAs/InGaP/InGaAs pHEMT structure has a narrower ohmic RTA process window than GaAs/AlGaAs/InGaAs pHEMT structure.

MICROSTRUCTURE OF THE OHMIC CONTACT

To understand this behavior, TEM and x-ray diffraction methods were used to examine the alloy grain formation, vertical and lateral penetration, and compositions of the ohmic alloys on the InGaP/InGaAs pHEMT structure. Shown in Fig. 3 is a scanning transmission electron microscopy (STEM) image for typical alloy grains. This sample was annealed at 420°C for 30 sec (sample 8L in Table II). One type of grain (denoted as A') is limited only in GaAs by the GaAs/InGaP interface. The other type of grain is made of two portions, in GaAs (denoted as A) and in InGaP (denoted as B). The InGaP etch stop layer under the n+ GaAs is very thin (~ 4 nm) and heavily doped, thus its impact was ignored in the current analysis.

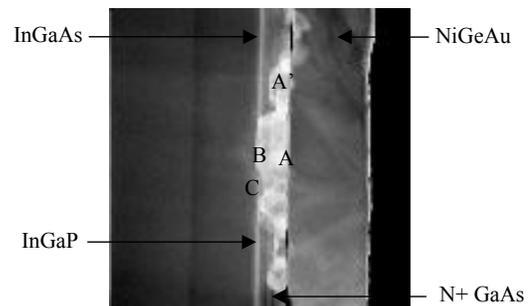


Fig. 3 A STEM image of several grains. Types A', A, B, and C are indicated.

Fig. 4 shows the EDS composition mapping of Ni, Ge, Ga, and As elements in the same grain as in Fig. 3. Ni distribution [Fig. 4(a)] displays two level type of feature defined by the GaAs/InGaP and InGaP/InGaAs interfaces, indicating that InGaP may impede Ni diffusion. Ge distribution in Fig. 4(b) is similar to the Ni, but with poor signal-to-noise ratio. It should be mentioned that the strong signal in the NiGeAu metal region of Fig. 4(b) is from Au instead of Ge, because Au L-line is very close to Ge K-line. In Fig. 4(c) Ga atoms have

depleted from the alloy grain and out diffused into the NiGeAu metal region. This is consistent with the concept of Ga-to-NiGe exchange during grain growth. Fig. 4(d) shows that all epi layers except InGaP are containing As element. However inside the alloy grain, As diffuses to InGaP layer.

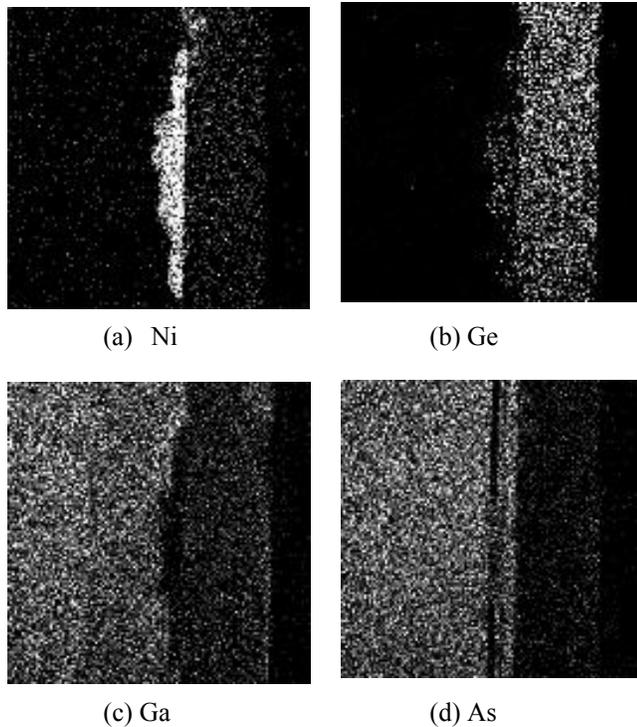


Fig. 4 EDS dot maps for (a) Ni, (b) Ge, (c) Ga, and (d) As elemental distributions. Ni distribution follows a staircase model limited by the hetero-interfaces. Ga however is depleted from these grains.

Seen in Fig. 5(a) is a dark field (DF) image at the contact region for the sample 8L (Table II) annealed at 420°C for 30 sec. The dark contrast above the InGaAs layer is observed (indicated by arrows) and determined to contain Au (type C grain). Au, Ni, Ga, and As are present, but no

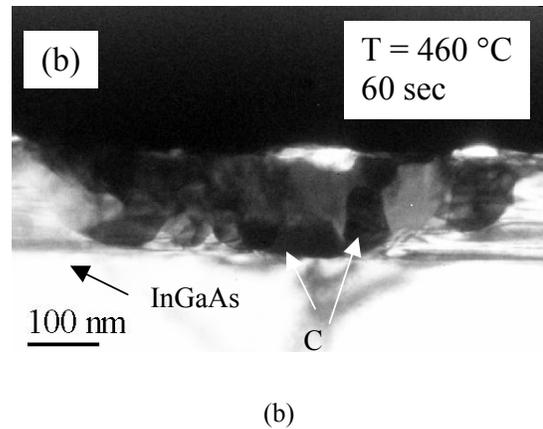
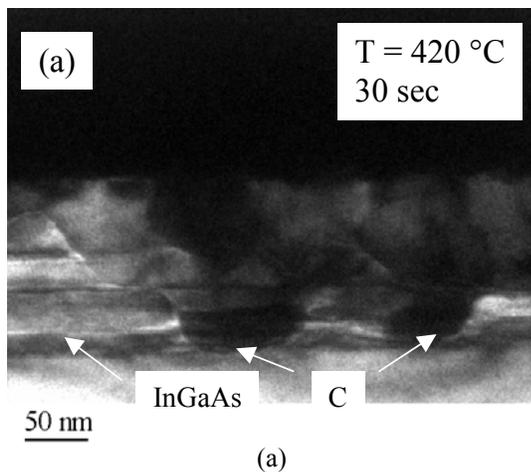


Fig. 5 (a) is a dark field image on sample 8L showing the Au-containing grains (type-C) above the InGaAs layer. (b) Shows additional vertically positioned type-C grains on sample 5R. The annealing conditions are labeled.

significant Ge. Such grains are similar to the non-ohmic grains, Au(Ga,As) seen in the AuGe/Ni on GaAs [3]. One key feature deserving attention is that type C grains preferably form above InGaAs. By increasing the annealing temperature to 460°C and annealing time to 60 sec, we found the Au containing grains expand laterally from ~ 80 nm at 420 °C 30 sec to ~ 150 nm at 460°C 60 sec, as seen in Fig. 5(b).

The compositions of elements Ni, Ge, As+P, Ga+In, and Au in type A, B, and C grains are derived from EDS analysis on samples 8L and 5R of Table II, and given in Table III. It can be seen that type A and B grains contain Ge, probably having the low resistivity phase NiGeAs; whereas type C grain contains Au, probably having the high resistivity Au-Ga phase. In addition, more Ni and Ge contents form in type A and B grains, and more Au forms in type C grain when RTA temperature and time increase from 420°C 30 sec to 460°C 60 sec.

Table III. Percentage content of Ni, Ge, As+P, Ga+In, and Au elements in the alloy grains of AuGe/Ni ohmic contacts annealed at 420°C for 30 sec and 460°C for 60 sec.

| Sample # | RTA Condition | Grain type | Ni | Ge | As + P | Ga + In | Au |
|----------|---------------|------------|----|----|--------|---------|----|
| 8L | 420°C, 30 sec | A | 46 | 9 | 43 | 2 | |
| 8L | 420°C, 30 sec | A' | 46 | 14 | 36 | 4 | |
| 8L | 420°C, 30 sec | B | 32 | 14 | 36 | 18 | |
| 8L | 420°C, 30 sec | C | 15 | | 23 | 16 | 46 |
| 5R | 460°C, 60 sec | A | 48 | 15 | 37 | | |
| 5R | 460°C, 60 sec | B | 47 | 18 | 30 | 4 | |
| 5R | 460°C, 60 sec | C | 7 | | 15 | 16 | 62 |

As we known, Rc_{n+} is dominated by the contact in n+ GaAs (i.e type A and A' grains) since majority of the electrical current flows through ohmic contacts in the n+ GaAs [Fig. 2(a)]. Type A and A' grains consist of NiGeAs which should form low resistance ohmic contacts to GaAs. At 420°C, the grains have essentially the same composition as at

460°C, but might have less population or less surface areas contacting to n+ GaAs. Therefore, higher R_{c_n+} was realized when the ohmic metal was annealed at 420°C. On the other hand for R_{on} , electrical current flows from the source electrode, vertically down through type A, type B, type C grains, passing the InGaAs channel laterally, and then to the drain electrode [Fig. 2(b)]. The resistance of type A and B grains should reduce at 460°C following the proposition discussed earlier. The difference in R_{on} would then be dominated by the difference in type C grains. It is known that Au containing grains (type C) generally lead to high resistance [3-5]. With the lateral expansion and formation of vertical type C grains at 460°C, one would expect an increase in R_{on} since more current may be blocked by type C grains.

CONCLUSIONS

NiGeAu ohmic contact as a function of RTA condition was investigated on InGaP/InGaAs pHEMT structure. It was found that the optimum RTA condition for device on-resistance is 420°C 30 sec, even though the optimum condition for n+ contact resistance is 460°C 60 sec.

Electron microscope examinations revealed three types of alloy grains: low resistivity NiGeAs containing types A and B, and high resistivity Au containing type C.

Chemical composition analysis showed that there were more Ni and Ge contents in the type A and B grains, and more Au content in the type C grain, with increasing RTA temperature and time. Because n+ contact resistance is mostly affected by type A grain, R_{n+} reaches lowest value while annealed at 460°C for 60 sec. However, annealing at 460°C for 60 sec has expanded type C grain size and increased its Au content, which degraded electrical contact to the channel and consequently increased on-resistance. Therefore, 420°C 30 sec becomes preferred RTA condition for on-resistance.

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ACRONYMS

pHEMT: pseudomorphic High Electron Mobility Transistor
FET: Field Effect Transistor
MESFET: Metal-Semiconductor Field Effect Transistor
TLM: Transmission Line Model
RTA: Rapid Thermal Anneal
TEM: Transmission Electron Microscope
STEM: Scanning Transmission Electron Microscope
EDS: Energy Dispersive Spectrum
CS1: Compound Semiconductor One fab in Motorola Inc.