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GaAs OHMIC CONTACTS FOR HIGH TEMPERATURE DEVICES*

J. A. Coquat and D. W. Palmer
Sandia Laboratories, Albuquerque, NM 87185

O. Eknoyan and W. B. Van der Hoeven
Texas A&M, College Station, TX 77843

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Abstract

Instrumentation requirements for geothermal wells, jet engines, and nuclear reactors have exceeded the high temperature capability of silicon devices. As one part of a program to develop high temperature compound semiconductor devices, four basic ohmic contact systems for n-type GaAs have been evaluated for contact resistance as a function of temperature (24-350°C) and time (at 300°C): Ni/AuGe; Ag/Si and Ag/Ni/Si; Al/Ge and Al/AlGe; and Au/Nb/Si and Pt/Nb/Si. Optimization of processing parameters produced viable high temperature contacts with all but the Al/Ge systems. Aging at 300°C changed the contact resistivity in only the Ag/Ni/Si contacts. Film adhesion was excellent for the Al/Ge, Ni/AuGe, and Ag/Si systems as measured with ultrasonic Al wire bond pull strengths. Lower adhesion was noticed with Nb/Si systems measured with gold wire bond pull strengths.

Introduction

The last four years have witnessed an expansion in development and implementation of solid state, high temperature microelectronics. Downhole instrumentation for evaluation of geothermal resources provided the initial impetus.[1] In 1975 a near term electronics goal of 275°C operation for 100 hours was chosen to meet the majority of then-envisioned geothermal requirements. As a spin-off of this DOE developmental effort and complementary industrial efforts, microelectronics for long term use at 200°C is now a commercial reality; a large advance from the long standard maximum use temperature of 125°C. In addition, some prototype hybrid microelectronics and monolithic silicon integrated circuits are being commercially fabricated and field tested for use in the 275-300°C temperature range.

More uses at higher temperature have been defined as the maximum operational temperatures of commercial electronics materials, components, and circuits have increased. Currently the largest industry using high temperature electronics is the oil and gas well service; their deepest and most hostile wells now reach 225°C. In comparison, geothermal wells with bottom temperatures around 350°C can produce electrical power with vastly greater thermodynamic efficiency than those below 275°C. The same quest for higher operational temperature is occurring above the ground. Microcomputer instrumentation for jet engines is under development for long term 260-300°C operation, while special jet exhaust transducer-amplifiers need 450°C capability.[2] Neutron flux detector-transmitters have been built for 250°C operation within nuclear reactors[3] where higher temperature reactor core monitoring is now required.

To help fulfill these electronics needs above 275°C, passive components (resistors, capacitors, and transformers) have recently been developed for operation to 500°C.[4] Although more development is needed to optimize the passive component properties at 500°C, it appears that the active devices are the barrier to rapid utilization of microelectronics above 275°C. In fact, for several years 275°C seemed the fundamental limit for silicon active devices. For example, the reverse leakage of a silicon bipolar diode becomes comparable to its forward signal current at this temperature. However, ongoing research has shown that silicon integrated devices are possible which operate in an analog mode at 325°C and digitally to 350°C.[5] The actual temperature limits depend on the degree of device performance degradation a circuit designer can accept.

In addition to upgrading of silicon devices, there are good reasons to also pursue the compound semiconductors. Larger bandgap semiconductors have a smaller density of thermally generated carriers at a given temperature. Tests run on GaAs diodes made at McDonnell Douglas and GaP diodes fabricated at both Sandia and Western Electric showed leakages at 350°C measured in nanoamperes compared to the milliamperes of comparably sized silicon diodes. However, during life tests on these III-V diodes and commercial GaAs MESFETs degradation was seen in the contact metallization; surface migration, phase change, and increase in specific contact resistivity were apparent.[6]

The most frequent metallization systems used on commercial GaAs are based on the AuGe eutectic, although an Al system is also available. AuGe can also be used with GaP, but AuSi and AuBe are more common.[7] None of these systems, as used commercially, appear to hold up at 300°C. Of course, these device contacts were designed for high frequency and perhaps high power applications, not for high temperature use.

There are many differences between an ohmic contact system optimized for high power and/or rf operation at room temperature ambient as compared to a low frequency, low power operation at high temperature ambient. The necessary specific contact resistance, bond pad size, aging rate, sintering temperature, and film adhesion are different:

1. Specific contact resistance of 10^{-6} to $10^{-7}\Omega\text{-cm}^2$ is required for rf devices whereas 10^{-5} to $10^{-6}\Omega\text{-cm}^2$ is satisfactory for low power needs. Extremely low contact and bond pad resistance is required by rf and high power devices to minimize local Joule heating.

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In contrast, contact resistances of 1Ω typically develop in present 300°C low power, low frequency hybrids with no resulting performance degradation. (For perspective, a contact pad that is 4 mils on a side and 10^{-4} Ω-cm^2 presents 1Ω).

2. The allowable contact size is related to the specific contact resistance. Rf devices require small area contact pads and electrodes to minimize capacitance and transit times, whereas features of audio devices can be 10 to 100 times larger. Therefore, an increased specific resistance can be countered by larger contact cross section in low frequency, high temperature devices.

3. Temperature tolerance for an rf device is typically measured in hours of operation when overstressed in a 150°C environment. In comparison, high temperature devices must operate for thousands of hours at 300-400°C ambient.

4. For both high frequency, high power and low frequency, low power devices the annealing temperature for contact formation must be higher than any further processing temperature and higher than any operational temperature. Since operation in the latter case is contemplated above 350°C, an annealing temperature of 450°C or higher is advisable. Furthermore, since the surface of GaAs can degrade within minutes above 600°C, the annealing temperature should lie between 450 and 600°C.

5. Contact adhesion is more critical in rf devices because of the need to use small bond areas and sub-mil diameter bond wires. Film adhesion can be an order of magnitude lower for low frequency devices having larger bond areas and using 3 mil bonding wire.

This investigation used as ~~a~~ contact criteria the following: 1) specific contact resistance of $\sim 10^{-5}$Ω-cm^2, 2) stability for 1000 hours at 300-400°C, 3) annealing temperatures well above 350°C, and 4) film adhesion supplying greater than 1 gram pull strengths for 1 mil wire. This paper will first present the basis for the metallization and dopant choices. Next, the simple experimental scheme for quick and inexpensive evaluation of these materials as ohmic contacts will be described. Last, the contact properties as a function of temperature and aging will be discussed.

Experimental

Material Choices

Over the last few years Sandia has performed 300°C aging tests on GaAs devices with AuGe and Al contacts, and on GaP devices with AuGe and AuSi-AuBe systems. All materials had degradation by surface migration, phase change, contact resistivity increase, and adhesion failure. For example, several mils of lateral spreading of the contact (migration) on the device surface took place with the Au based systems after a few hundred hours at 300°C. In addition, precipitation of compounds (phase change) occurred in the AuGe contacts. Recent investigations[9] of GaAs contacts at high temperature have identified several mechanisms which lead to failure: sensitivity to mismatched expansion coefficients because of the large operational temperature range, loss of contact integrity when the operating temperature is comparable to the eutectic temperature, and rapid diffusional degradation at high temperature.

Based on the results of these contact aging studies and the four contact criteria, the following contact systems have been investigated:

1. AuGe was included in this study as a point of comparison with the commercial contact metallizations. The film was deposited in the form Ni/AuGe, where the nickel layer was intended to improve the adhesion of the AuGe by wetting the GaAs surface.

2. AlGe was tested because of its higher eutectic temperature (424 compared to 356°C for AuGe). In addition, the possibility exists of an all aluminum system, with Al schottky contacts, aluminum bond wires, and AlGe die down preforms.

3. The eutectic temperature of silver with common dopants (Si, Sn, Ge) are higher than those of gold (for example, AgSi is 830°C whereas AuSi is 370°C). Moreover, silver has a comparable diffusion rate in GaAs to that of gold.[8] To complete the silver contact system a silicon dopant layer was used to benefit both from the high AgSi eutectic temperature and the slow diffusion rate of Si in GaAs. A nickel layer was included in one variation of this system (Ag/Ni/Si) to improve adhesion.

4. Niobium was used in an effort to match the thermal expansion coefficient of the contact with GaAs over the intended large temperature range. Two variations, Pt/Nb/Si and Au/Nb/Si, were tested.

Bulk substrates were used instead of epitaxially grown layers in order to eliminate the quality of the particular epitaxial material as a variable. This material was purchased from Morgan and Crystal Specialties. As a consequence of using bulk substrates, aging effects of these contact systems on an np interface cannot be measured. These effects will be independently measured to ensure long life of device junction interfaces lying beneath contacts. Only n-type material has been studied to date. Two basic doping levels were used, undoped (10^{16} cm^{-3}) and moderately doped (5×10^{17} cm^{-3}), in order to span the bulk doping range which contacts encounter.

Contact Resistance Measurement Method

The use of bulk GaAs material eliminated many common contact resistance measurement schemes that rely on current flow restriction to the two dimensional epilayer.[10,11] Thus, it was necessary to use a method that is more tolerant to material thickness. A common problem with bulk methods[12] is the difficulty in distinguishing between the contact resistance and the series resistance of the semiconductor. To circumvent this, the concentric ring pattern shown in Figure 1 and a four-wire measurement technique have been used.

A constant current (I) is applied between the first and second rings developing a net voltage which includes a potential difference (V_{CR}) across the non-zero contact resistance of the first contact ring to GaAs semiconductor interface. All current flows radially and symmetrically out from the first ring and thus the bulk material surface interior to this ring is at the same potential as that of the bulk surface immediately below the first ring. Using a high impedance voltmeter, the potential from the first ring to the interior metal dot is monitored. This measurement is equal to V_{CR} provided negligible current is flowing interior to the first ring due to the voltmeter or assymmetry in current I. The specific ohmic contact resistance is then given by

$$\rho_c = \frac{V_{CR}}{I} \times A$$

where A = the area under the first ring.

Procedure

GaAs substrates were subjected to a standard solvent cleaning, including a 2-minute HCl etch. All metallization was performed in an E-beam vacuum deposition system. Samples were baked out at 300°C for an hour in vacuum and then cooled to 150°C for deposition. Deposition was accomplished at 10^{-6} Torr. Films were deposited both in layered and alloy form; for example, on one set of substrates a film of Ge was deposited followed by a film of Al, and on another set, a film of eutectic alloy AlGe was deposited. Pattern masking was accomplished using 1350J photoresist. Wet chemical etching was used for Al, Au, Ag, and Ni. Gold etch was used for the eutectic AuGe and Al etch for AlGe. Plasma CF_4 and CF_4/O_2 etching was used for Si, Ge, and Nb. Ion milling was needed for Pt removal. Annealing was performed in a tube furnance with a flow of forming gas (10% H_2). The furnance temperature was controlled to within 5°C. Samples from each contact system were annealed at three different temperatures. Electrical measurements were performed on a probe station with a substrate heater. A constant 10 mA current was injected between the inside and middle ring, while the voltage was measured between the central dot and the inside ring (see Figure 1). To ensure radial symmetry of the current flow, multiple probe contacts and thick metallizations were used. Samples were aged in a 300°C recirculating air oven without current loading. Contacts that retain useful properties for 1000 hours are then tested at 400°C.

Results and Discussion

The specific material thicknesses, annealing temperature , and deposition rates are listed in Table I. The systems varied in their sensitivity to annealing time and temperature with Ni/AuGe being the most tolerant and Nb/Si the least (see Tables II-IV). All systems except the AlGe showed initial contact resistivity from 24 to 350°C of $\sim 10^{-5}\Omega\text{-cm}^2$. Nickel was used in two systems as a wetting agent, however, in all cases but one, there was good wetting and adhesion. The exception occurred with the Nb/Si system. Whether this was caused by poor wetting or thermal mismatch is not yet known. Aging in an air recirculating oven at 300°C produced no significant contact resistance changes except in the Ag/Ni/Si system where the resistance increased by a factor of 5 over 300 hours.

Reasonable specific contact resistances have not been achieved with the AlGe system despite many variations on fabrication technique. Measured values were greater than $10^{-2}\Omega\cdot\text{cm}^2$. Good film adhesion was always achieved whether a single alloy film or consecutive Al and Ge films were deposited. Variation of annealing temperature and contact resistance monitoring during annealing indicated an optimum processing temperature below 400°C. Unfortunately, this optimum temperature is lower than the envisioned device operational temperature. Although the physics of the inadequate contact alloying is not yet understood, it is clear that the Al/Ge system was not compatible with processing used in this study.

Film adhesion was ascertained by affixing fine wire bonds and measuring the pull strengths to failure. Ultrasonic aluminum wire bonding was tried on all contact materials. A Kulicke and Soffa 484 bonder with a Microswiss Titanium Carbide Concave Tool No. 423-10-03 was used with 1 mil Al wire (1% Si) having a tensile strength of 15 grams. The contact samples were patterned and annealed before bonding but had seen no aging. Excellent adhesion was measured for Al/Ge, Ag/Si, and Ni/AuGe systems with an average pull strength of 10 grams. For these three systems the useful range of bonding parameter was large; the ultrasonic power and duration could be adjusted by a factor of 2 with only a 40% decrease in pull strength. Bond failure occurred both at the contact film to GaAs interface and at the bond pad heel. In contrast to the excellent adhesion measured in these three systems, the two variations of the Nb/Si system could not be ultrasonically bonded with aluminum wire. Surface contamination resulting from ion milling of the Pt certainly contributed to this problem; moreover spalling of the semiconductor surface during bonding attempts suggests a high surface stress exists in these films. Internal stress was again implicated when samples annealed above 600°C showed edge peeling. For this reason a thermocompression gold wire bond pull strength test was used. Pull strengths greater than 1 gram were achievable, but strength variability existed from sample to sample. Processing variations (deposition temperature, film thickness, annealing time) are being performed to optimize this marginal adhesion.

Table III reveals that the ohmic resistance for samples obtained from wafer No. 6 (doping 5×10^{17} cm^{-3}) are almost an order of magnitude smaller than those obtained from wafer No. 3 (doping 10^{16} cm^{-3}). This is explained by the fact that current flow at the interface is assisted by a tunneling mechanism across the barrier width which is made narrower by the higher doping in the substrate.

In summary, considerable optimization of parameters and testing remain in qualifying a high temperature ohmic contact system. Nonetheless, the 300°C results for Ni/AuGe and Ag/Si systems satisfy the criteria of adhesion, contact resistivity, high annealing temperature, and high temperature aging stability. The 356°C eutectic temperature of AuGe, however, poses a potential problem being within the operational temperature range. Better adhesion and bondability must be obtained in Au/Nb/Si and Pt/Nb/Si contacts and lower specific resistivity in the Al/Ge and Al/Ni/Ge contacts before either can be considered for high temperature. The results of 400°C aging will be reported in the presentation.

Acknowledgment

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Table I

METAL THICKNESS AND EVAPORATION RATE OF CONTACT SYSTEMS TESTED

N
A

Materials	Thickness (A)	Evaporation Rate (A/sec)
Ni/AuGe	500/1500 400/2000 400/1600 800/3000	3/3
Ag/Si	4000/800	10/2
Ag/Ni/Si	10,000/700/1000	10/3/3
Pt/Nb/Si	4000/2000/600	3/3/3
Au/Nb/Si	8000/2000/1000	10/3/3
Al/Ge	10,000/1000	40/3
Al/AlGe	5000/5000	40/3

Table II

Ag/Si METALLIZATION

Alloying		Specific Ohmic Contact, Ω-cm^2		
Temp (°C)	Time (min.)	Room Temp.	90 hrs at 275°C	147 hrs at 300°C
600	5	3.3×10^{-5}	3.1×10^{-5}	3.6×10^{-5}
590	3	2.5×10^{-5}	3.9×10^{-5}	5.8×10^{-5}
575	5	3×10^{-4}	1.3×10^{-3}	6.5×10^{-2}
550	5	3×10^{-5}	9×10^{-5}	2.7×10^{-5}
Ag/Ni/Si				
600	3	7.6×10^{-5}	1.6×10^{-4}	2.5×10^{-4}

Table III

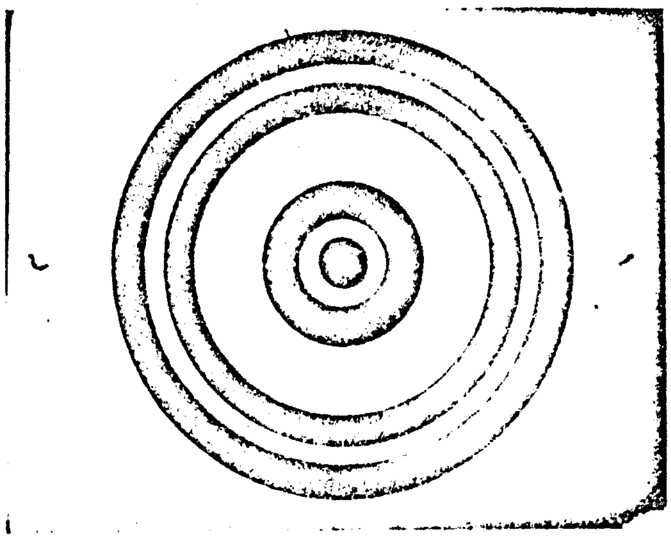
Ni/AuGe METALLIZATION

Wafer No.	Alloying		Specific Ohmic Contact, Ω-cm^2	
	Temp. (°C)	Time (min.)	Room Temp.	Aged at 300°C
3	500	5	6.1×10^{-4}	3.6×10^{-4}, 245 hrs
6	500	5	3.2×10^{-5}	2.3×10^{-5}, 245 hrs
3	450	10	4.7×10^{-4}	4.2×10^{-4}, 145 hrs
6	450	10	2.0×10^{-5}	2.4×10^{-5}, 145 hrs
3	450	5	4.7×10^{-4}	3.5×10^{-4}, 162 hrs
6	450	5	3.0×10^{-5}	2.6×10^{-5}, 162 hrs

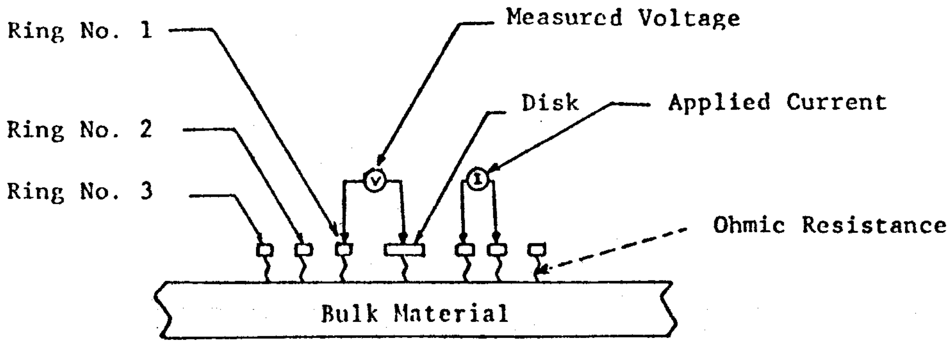
Table IV

Au/Nb/Si METALLIZATION

Alloying		Specific Ohmic Contact, Ω-cm^2	
Temp (°C)	Time	Room Temp.	90 hrs. at 300°C
600	5	7.7×10^{-3}	-
550	5	5×10^{-5}	7×10^{-5}
500	10	1.9×10^{-1}	-



Microscope Photograph of Contact Ring Pattern
(Outer Ring - 66 mill O.D. diameter)



Schematic of Contact Rings and Measurement Probe Locations

Figure 1