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14. ABSTRACT
Alloys of aluminum (Al) have previously been used as ohmic contacts to p-type SiC, however the characteristics and performance of these contacts is drastically affected by the type and composition of the Al alloy. This work examined alloys of Al and titanium (Ti) as a function of alloy composition with the goal of determining the composition which would yield the best ohmic contact to p-type SiC as characterized by a low specific contact resistance, a limited reaction between the metal alloy and the SiC, and reproducibility of contact parameters. After examining 4 Al-Ti alloys, it was determined that a 70/30 weight percent alloy composition of Al and Ti produced low resistance, reproducible ohmic contacts with minimal reaction to p-type SiC. It is further noted that a liquid phase of the alloy must be present during the anneal that forms the ohmic contact. Although this work was performed on heavily doped 4H material, previous work done by the authors supports the conclusion that these results will be valid on all polytypes of SiC with a corresponding increase in specific contact resistance as the doping level of the semiconductor decreases.

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Final Report on ONR Grant No. **N00014-99-0785** entitled "Ohmic Contacts to P-Type SiC"

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Introduction

Al-Ti alloys have been used for many years now as ohmic contacts to p-type SiC [1]. However, a review of the literature shows that the underlying mechanisms responsible for ohmic contact formation using Al-Ti alloys have yet to be published. An examination of the binary Al-Ti phase diagram shows that there are many different phases present prior to any reaction of the metal alloy with the SiC (see Figure 1). Since initial attempts to form ohmic contacts to p-type SiC primarily involved Al, initial studies of Al-Ti alloys tended to be Al rich. An alloy which has been closely studied and characterized is a 90/10 (weight percent) Al-Ti alloy which upon annealing at 1000 °C for several minutes is capable of producing low resistance ohmic contacts [2]. **The goal of the work funded by ONR was to determine the best Al-Ti alloy for use as an ohmic contact to p-type SiC.** This report summarizes results previously obtained using a 90/10 Al-Ti alloy and includes results for three additional alloys: 70/30, 60/40, and 19/81. These compositions are in weight percent, and for convenience they are marked on the Al-Ti phase diagram in Figure 1, which is in atomic percent.

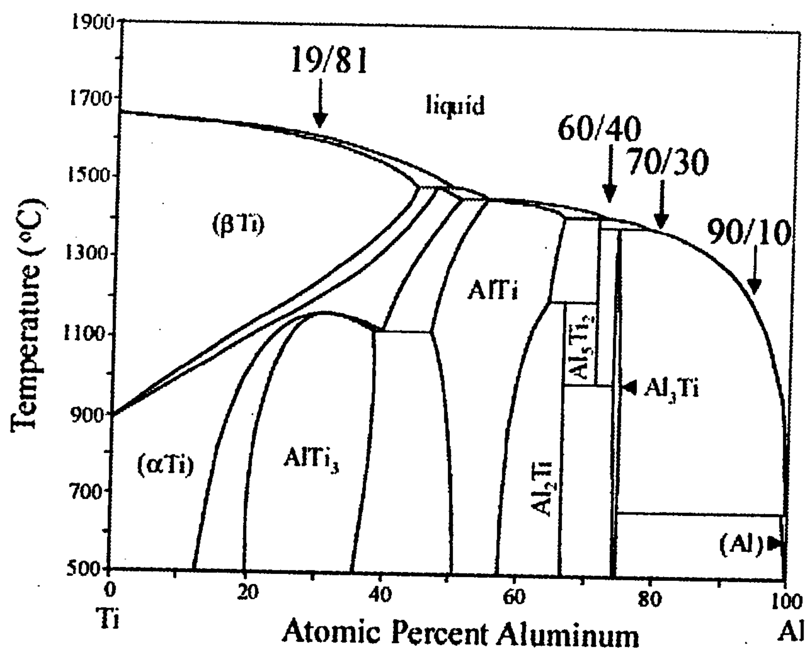


Figure 1. Al-Ti binary phase diagram.

Summary of Previously Obtained 90/10 Alloy Results

Previous work using an Al-Ti alloy that is 90% Al and 10% Ti yielded low resistance ohmic contacts to heavily doped p-type SiC [2]. This work was performed on the 6H polytype although it is believed that the results are relatively polytype insensitive. One noteworthy feature of this particular alloy is the relatively large Al loss during typical anneals of 1000 °C for a few minutes. An examination of the Al-Ti phase diagram shows that at 1000 °C, the 90/10 composition consists of both a solid phase ($TiAl_3$) and a liquid phase that is Al rich. The vapor pressure of pure Al at 1000 °C is calculated to be $2x10^{-4}$ Torr [3], so it is not surprising that volatile Al is lost in large amounts during the anneal. Too much Al loss during the anneal results in films that have very large post anneal sheet resistances which may be so large that the film essentially becomes non-conducting. It was found experimentally that by sputtering an Al-Ti layer with a minimum thickness of approximately 2500 Å, sufficient Al was left in the contact after the anneal and the post anneal sheet resistance often even decreased a few ohms/square. A 2500 Å or greater thick layer of a 90/10 film was found to produce low resistance ohmic contacts to very heavily doped (> 10^{19} cm^{-3}) p-type SiC. It was observed however that there could be considerable electrical variation in the contacts both in terms of the contact resistance and the metal sheet resistance after annealing. Further physical analysis of the contact was performed by chemically etching away the contact (as described in [2]) and performing scanning electron microscopy (SEM) and atomic force microscopy (AFM) on the freshly exposed SiC surface. This experiment revealed the morphology of the previously buried metal/semiconductor interface, which for the 90/10 alloy was characterized by spiking of the metal into the semiconductor. Because only a small number of spikes are contained in the active region of a contact, the interfacial morphology is a possible contributing factor to the poor reproducibility of the electrical characteristics of the contacts. The surface of the SiC that was exposed after the annealed 90/10 alloy was etched away will be compared later to other alloy compositions. Electrical results for all the Al-Ti alloys studied are summarized in Table 1.

Table 1. Summary of results obtained from different Al-Ti alloy compositions. Specific contact resistance is denoted by r_c while metal sheet resistances before and after a two minute 1000 °C anneal are denoted by R_{sh} before and R_{sh} after respectively.

alloy	typical r_c	doping	thickness	R_{sh} before	R_{sh} after
90/10	1.1E-5 Ωcm^2	1.3E19 cm^{-3}	2500 Å	<6 Ω/□	<1 Ω/□
70/30	1.5E-4 Ωcm^2	7E18 cm^{-3}	1900 Å	<50 Ω/□	<30 Ω/□
60/40	not ohmic	7E18 cm^{-3}	3600 Å	<30 Ω/□	<10 Ω/□
19/81	not ohmic	7E18 cm^{-3}	3100 Å	<70 Ω/□	<40 Ω/□

While Table 1 summarizes typical results obtained using 4 different Al-Ti alloys, in this work funded by ONR, a total of 26 different samples were prepared for analysis which included semiconductor sheet resistance measurements, metal thickness and sheet resistance measurements, specific contact resistance measurements, Rutherford Backscattering Spectrometry (RBS) measurements, scanning electron microscopy (SEM) measurements, and atomic force microscopy (AFM) measurements. Results for all 26 samples have been omitted for the sake of brevity. Note also that in Table 1, the SiC doping in the 90/10 alloy work was higher than that used for the 70/30, 60/40, and 19/81 work. It will be shown later that this accounts for the lower specific contact resistances typically achieved using the 90/10 alloy.

70/30 Alloy Results

As discussed previously, although contacts using a 90/10 alloy were observed to form low resistance ohmic contacts to p-type material, the process used was found to be somewhat irreproducible in that unacceptable variations in contact resistance, sheet resistance and other parameters were observed. In an attempt to find a process that was more reproducible, a different Al-Ti alloy was studied. Because of the large percentage of a liquid phase in the 90/10 alloy at annealing temperatures of 1000 °C, a less Al rich alloy was chosen. It was desired however to remain in the same region of the Al-Ti phase diagram but to reduce the amount of the liquid phase present. Therefore, a 70/30 alloy was chosen. This composition is also indicated on the phase diagram in Figure 1.

Results using the 70/30 alloy were encouraging. The irreproducible aspects of the 90/10 process seemed to be reduced significantly while still providing very low resistance ohmic contacts. Additionally, it was found that the initial thickness of the deposited contact did not have to be as thick as for the 90/10 alloy to control the Al loss during the anneal and prevent a large increase in the metal sheet resistance. Typical results for contacts using a 70/30 alloy are also shown in Table 1. Although an examination of Table 1 may lead one to conclude that the 70/30 alloy does not yield contact resistances as low as the 90/10 alloy, it should be noted that the p-type doping level used in the 90/10 alloy was higher than that used for the 70/30 work. Once the doping reaches the 10^{19} cm^{-3} range, the specific contact resistance is a very strong function of the semiconductor doping. Figure 2 shows a theoretical plot of specific contact resistance verses doping for 6H-SiC [1]. Although the plot was generated for 6H material, these results appear to be relatively polytype insensitive, therefore experimental results obtained using a 70/30 alloy on 4H are shown along with a typical 90/10 (6H) result at a higher doping. The 6H value shown (also given in Table 1) gives a typical best case result (contact resistance) which is in the low 10^{-5} ohm-cm^2 range. As stated earlier, it is not uncommon when using a 90/10 alloy to encounter much higher specific contact resistances or even contacts that are not completely ohmic. The 70/30 contact exhibits much more reproducibility as evidenced by the three points which all fall very near the theoretical curve.

In addition to the 70/30 results shown, p-type SiC samples from Purdue University were metallized at Murray State using a 70/30 alloy and at Penn State using a sequence of Al and Ti layers that would yield an Al to Ti ratio of 70 to 30. These samples were returned to Purdue for continued processing and measurement of specific contact resistances. Results from these samples were in agreement with the results shown in Figure 2.

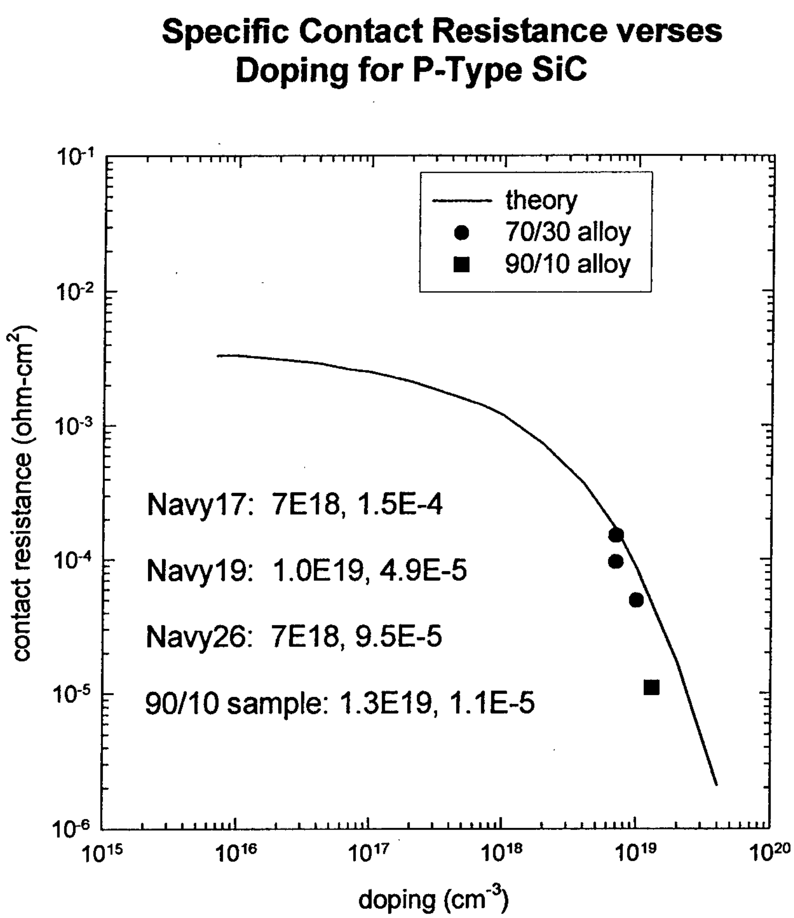


Figure 2. Theoretical curve of specific contact resistance verses doping for p-type SiC along with a typical (best case) 90/10 and three 70/30 Al-Ti alloy results.

60/40 and 19/81 Alloy Results

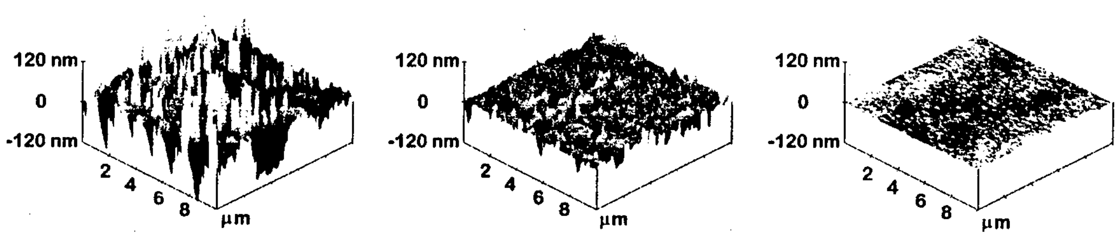
In addition to the 90/10 and 70/30 alloys, two different Al-Ti compositions were chosen which represented distinct regions of the Al-Ti phase diagram. The 60/40 alloy consists of a mixture of intermetallics, including the $TiAl_3$ phase while the 19/81 alloy consists of the Ti_3Al phase. Neither of these alloy compositions has any liquid phase present at 1000 °C. Samples were fabricated using these alloys as contact materials. After annealing at 1000 °C for 2 minutes in vacuum, neither of these alloys was found to produce ohmic contacts as occurred when using a 90/10 or 70/30 alloy. While continued annealing at subsequently higher temperatures (e.g. 1050 °C, 1100 °C, etc.) was found to decrease the overall resistance of the contacts as evidenced by I-V curves, the contacts never exhibited ohmic behavior. The maximum anneal attempted to induce ohmic behavior was 1200 °C for 2 minutes.

Physical Analysis of the Contacts

The electrical results indicated that ohmic behavior was observed in contacts which had a liquid phase present at the anneal temperature of 1000 °C. In contacts which had no liquid phase present, the electrical characteristics were non-ohmic (leaky Schottky). An examination of the surfaces of the different alloys was undertaken to try and understand what effect the presence of the liquid phase had on the metal/semiconductor interface. It was initially hypothesized that the liquid phase would lead to spiking of the alloy into the SiC much like pure Al will spike and penetrate pure Si. Figure 3 shows SEM scans of the SiC surface after etching away the annealed contact alloy for three of the Al-Ti alloys studied: 90/10, 70/30, and 60/40. Figure 4 shows AFM scans of the SiC surface for the same three samples.

(a) 90/10 (b) 70/30 (c) 60/40

Figure 3. SEM image of the SiC surface revealed after the annealed (a) 90/10, (b) 70/30, and (c) 60/40 contacts were etched away. All samples were annealed at 1000 °C for 2 minutes in vacuum.



(a) 90/10 (b) 70/30 (c) 60/40

Figure 4. AFM image of the SiC surface revealed after the annealed (a) 90/10, (b) 70/30, and (c) 60/40 contacts were etched away. All samples were annealed at 1000 °C for 2 minutes in vacuum.

The images in Figures 3 and 4 clearly show the degree of the reaction that occurs upon annealing an Al-Ti alloy at 1000 ^{0}C on SiC. The figures also show that the severity of the reaction differs greatly depending on which Al-Ti alloy is used. While the 60/40 alloy shows the least amount of reaction with the SiC, the reaction is not sufficient to produce ohmic behavior.

Summary and Conclusions

After an examination of 4 different Al-Ti alloys, it is clear that only the alloys with a liquid phase present at the anneal temperature considered here (1000 °C for 2 minutes) produce ohmic contacts on heavily doped p-type SiC. It has further been shown that these alloys spike into the SiC. It has not been established whether the spiking leads to an increase in the Al doping of the SiC or rather that the spikes themselves behave as field emitters with a substantially increased leakage current that macroscopically manifests itself as an ohmic contact when the effects of multiple spikes are averaged. However, it seems unlikely that at 1000 °C the Al can diffuse onto acceptor sites to create heavily doped p-type regions that allow enhanced current flow due to tunneling. Nevertheless, it is clear that the spikes present after annealing the liquid containing Al-Ti alloys are necessary to produce low resistance ohmic contacts to heavily doped p-type material. Previous work by the authors further supports the conclusion that these liquid containing alloys will produce ohmic contacts with an increasing specific contact resistance as the doping level of the semiconductor decreases. The remaining challenge is to further control the spiking so that the desirable ohmic electrical behavior can be retained while controlling the degree of the spiking so that shallow reproducible contacts can be formed. It is believed that the 70/30 alloy represents the best solution toward this end.

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