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Contact Resistance of Nickel/Germanium/Gold, Palladium/Germanium/Titanium/Platinum, and Titanium/Palladium Ohmic Contacts to Gallium Arsenide and Its Temperature Dependence from 4.2 to 350K

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ARL-TR-944

August 1996

NOTICES

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REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1996	Technical Report

4. TITLE AND SUBTITLE
CONTACT RESISTANCE OF NICKEL/GERMANIUM/GOLD, PALLADIUM/GERMANIUM/TITANIUM/PLATINUM, AND TITANIUM/PALLADIUM OHMIC CONTACTS TO GALLIUM ARSENIDE AND ITS TEMPERATURE DEPENDENCE FROM 4.2 TO 350K

5. FUNDING NUMBERS

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7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
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Physical Sciences Directorate (PSD)
ATTN: AMSRL-PS-DB
Fort Monmouth, NJ 07703-5601

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-944

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION / AVAILABILITY STATEMENT
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12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The specific contact resistance, r_c, and contact resistance, R_C, of NiGeAu and PdGeTiPt Ohmic contacts to n-GaAs and TiPd and PdGeTiPt Ohmic contacts to p+-GaAs were determined as a function of temperature between 4.2 and 350K. The low r_c obtained for some of the contacts at 4.2K implies that much of the total contact resistance measured at 4.2K in 2DEG structures lies across the n-n heterojunction(s) in series with the metal semiconductor junction. Although NiGeAu contacts have a lower contact resistance to n-GaAs, PdGeTiPt contacts, which have much better edge definition, can be substituted for the NiGe Au when they are properly annealed. Also, low resistance contacts can be made to heavily p-doped GaAs at 4.2K using either TiPd or properly annealed PdGeTiPt contacts. r_c for the TiPd contacts annealed at 350°C for 15s and at 395°C for 90s, and the 350°C/15s p-PdGe-TiPt contact fit the field emission model, and the 395°C/90s NiGeAu, 350°C/15s n-PdGeTiPt, and 395°C/90s p-PdGeTiPt contacts can be described by the thermal field emission mode. However, the 350°C/15s NiGeAu and 395°C/90s n-PdGeTiPt contacts have a much larger temperature dependence that can best be described by tunneling to deep states near the metal-semiconductor interface.

14. SUBJECT TERMS
Contact resistance; nickel/germanium/gold; palladium/germanium/titanium/platinum; titanium/palladium; temperature dependence

15. NUMBER IF PAGES
19

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

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SYMBOLS, ABBREVIATIONS AND ACRONYMS

FE	field emission
GaAs	gallium arsenide
i-V	current - voltage
mA	milliamperes
MBE	molecular beam epitaxy
NiGeAu	nickel germanium gold
nm	nanometer
OMVPE	organometallic vapor phase epitaxy
PdGeTiPt	palladium germanium titanium platinum
r_c	specific contact resistance
R_c	contact resistance
R_{sh}	sheet resistance
RTA	rapid thermal annealing
s	seconds
SIMS	secondary ion mass spectroscopy
TDE	thermal defect emission
TFE	temperature field emission
TiPd	titanium palladium
TLM	transmission line measurement
μm	micron
2DEG	two dimensional electron gas
2DHG	two dimensional hole gas

CONTACT RESISTANCE OF NiGeAu, PdGeTiPt AND TiPd OHMIC CONTACTS TO GaAs AND ITS TEMPERATURE DEPENDENCE FROM 4.2 TO 350K

ABSTRACT

The specific contact resistance, r_c, and contact resistance, R_c, of NiGeAu and PdGeTiPt Ohmic contacts to n-GaAs and TiPd and PdGeTiPt Ohmic contacts to p^+-GaAs were determined as a function of temperature between 4.2 and 350K. The low r_c obtained for some of the contacts at 4.2K implies that much of the total contact resistance measured at 4.2K in 2DEG structures lies across the n-n heterojunction(s) in series with the metal semi-conductor junction. Although NiGeAu contacts have a lower contact resistance to n-GaAs, PdGeTiPt contacts, which have much better edge definition, can be substituted for the NiGeAu when they are properly annealed. Also, low resistance contacts can be made to heavily p-doped GaAs at 4.2K using either TiPd or properly annealed PdGeTiPt contacts. r_c for the TiPd contacts annealed at 350°C for 15s and at 395°C for 90s, and the 350°C/15s p-PdGe-TiPt contact fit the field emission model; and the 395°C/90s NiGeAu, 350°C/15s n-PdGeTiPt, and 395°C/90s p-PdGeTiPt contacts can be described by the thermal field emission model. However, the 350°C/15s NiGeAu and 395°C/90s n-PdGeTiPt contacts have a much larger temperature dependence that can best be described by tunneling to deep states near the metal-semiconductor interface.

INTRODUCTION

It is of interest to know the value of the specific contact resistance, r_c, at temperatures $\leq$4.2K as it is in this temperature regime that many of the studies of the physics of the 2 dimensional electron gas, 2DEG, are performed.[1] The total contact resistance has been measured,[2] but it was not possible to determine what fraction was due to the resistance across the metal-semiconductor junction and what fraction was due to the resistance of the n-n heterojunction(s) in series with it. Another important consideration for Ohmic contacts to 2DEGs is their lateral extension. This is particularly true for devices relying on the quantum interference effect as in this case it is desirable to have contacts close to each other. Thus, it would be helpful to know if, e.g., the nonalloyed n-PdGeTiPt[3-5] contact can be substituted for the more frequently used alloyed n-NiGeAu[6-10] contact.

Although most of the 2D carrier gas GaAs/AlGaAs structures that are studied are electron gas structures, there is also some interest in transport in hole gases.[11] As a result there is also interest in Ohmic contacts to p-type GaAs at and below 4.2K. Of particular interest are contacts with good edge definition because 2DHGs are often created by electric fields which require self aligned gate technology.[11]

We have shown that PdGeTiPt can be used as an Ohmic contact to heavily doped p-type as well as n-type GaAs.[4,8] The n-type contact has a small contact resistance after short time, low temperature anneals, whereas the contact resistance for the p-type is small after longer time, higher temperature anneals. We have attributed this behavior to an initial rapid out-diffusion of Ga and the subsequent occupation of the Ge in the Ga sites, and a later out-diffusion of As and the subsequent occupation of the Ge in the As vacancies.[4,8] This hypothesis can be examined by measuring r_c as a function of temperature for PdGeTiPt contacts to both types of material and comparing the results with those of the NiGeAu contact to n-type GaAs and TiPd[8,12] contacts to p-type GaAs. In this paper we measure r_c and the contact resistance, R_c, as a function of temperature between 4.2 and 350K for the four different types of contacts that were annealed at 350°C for 15s or at 395°C for 90s.

RESULTS AND DISCUSSION

A 0.5 μm GaAs buffer layer followed by a 0.3 μm heavily doped layer were grown by MBE (n-type) or OMVPE (p-type) on a 2" semi-insulating GaAs wafer. The n-type films were Si doped to 2 x 10^{18} cm^{-3}, and the p-type films were C doped to 5 x 10^{19} cm^{-3}. 100 x 150 μm pads with spacings of 5, 10, 15 and 20 μm were deposited and each set of pads was isolated by a mesa etch using standard photolithographic lift-off techniques. The layer thicknesses for the NiGeAu were 5, 20 and 580 nm; for the PdGeTiPt they were 20, 40, 40 and 30 nm with a 500 nm Au contact layer; and for the TiPd they were 75 and 75 nm with a 500 nm Au contact layer. Each wafer was cut into eighths and subjected to different types of anneals. r_C, R_C and the sheet resistance, R_{sh}, were automatically computed using the TLM method[13] by forcing 10 mA between pads and measuring the voltage. Of the approximately 150 TLM patterns on each die a few with low contact resistances were probed further for their linearity by plotting their i-V curves between ±0.2 V.

One set of the four different types of contacts had been subjected to a rapid thermal anneal (RTA) for 15 sec at 350°C and another set had been subjected to an RTA for 90 sec at 395°C. Two leads were wedge or ball bonded to each pad of the TLM patterns that were selected for four point probe measurements that were done manually. Measurements were made at room temperature, 295K, and at 77 and 4.2K by submerging the wedge bonded samples into liquid nitrogen or liquid helium. Measurements were made on the ball bonded samples as a function of temperature from about 5K to 350K in a liquid helium circulation system. Measurements were made in the circulating system only on the NiGeAu sample annealed at 350°C for 15 sec; the TiPd sample was considered to be too routine, and the PdGeTiPt pads annealed for this short period of time would often lift off when they were ball bonded. Obtaining PdGeTiPt samples that would adhere to the substrate was, in fact, such a tedious process that only three of the four pad spacings could be used for the 395°C/90s n-PdGeTiPt contact because one of the end pads had lifted off.

r_c, and R_c for the submerged samples determined at 295, 77 and 4.2K are listed in Table 1. r_c for the four 395°C/90s and the 350°C/15s NiGeAu samples is plotted as a function of temperature in Fig. 1. The 350°C/15s n-NiGeAu contact is Ohmic at room temperature and increases rapidly as the temperature decreases, but is not Ohmic for T < 175K. The resistances between the pads continue to increase as the temperature decreases, but, as shown in Fig. 2a, they increase at different rates. The n-PdGeTiPt 395°C/90s contact behaves in a similar way as it ceases to be Ohmic for T < 150K, and the resistances increase at different rates as T decreases as is shown in Fig. 2b.

Except for the n-NiGeAu, all of the contact resistances at 4.2K for the contacts annealed at 350°C for 15s are much lower than those obtained for the 2DEG structure.[2] With the exception of the n-PdGeTiPt the same thing can be said for the contacts annealed at 395°C for 90s. This implies that much of the contact resistance measured for the 2DEG structures lies elsewhere - most probably at the 2DEG interface.

It is interesting to note that if the contact has a low r_c at room temperature, it will also have a relatively low value at 4.2K. This is particularly true for the p-TiPd contact where r_c decreases very slowly as the temperature increases much as is

Table 1. The specific contact resistance, r_C, and contact resistance, R_C, of the four different contacts at room temperature, submerged in liquid N, or submerged in liquid He that were annealed at 350°C for 15 sec or 395°C for 90 sec.

	r_C ($\mu\Omega\cdot cm^2$)			R_C ($\Omega\cdot mm$)		
	295K	**77K**	**4.2K**	**295K**	**77K**	**4.2K**
			350°C/15s anneal			
n-PdGeTiPt	.346	2.48	3.32	.0308	.084	.101
n-NiGeAu	28.7	-	-	.262	-	-
p-PdGeTiPt	1.17	1.86	1.86	.069	.0713	.075
p-TiPd	.240	.301	.301	.0293	.0285	.0281
			395°C/90s anneal			
n-PdGeTiPt	8.20	28.8	92.1	.156	.300	.573
n-NiGeAu	.659	.579	.740	.0405	.0375	.0425
p-PdGeTiPt	.539	1.51	2.46	.0476	.0655	.0830
p-TiPd	.302	.502	.502	.0405	.0458	.0458

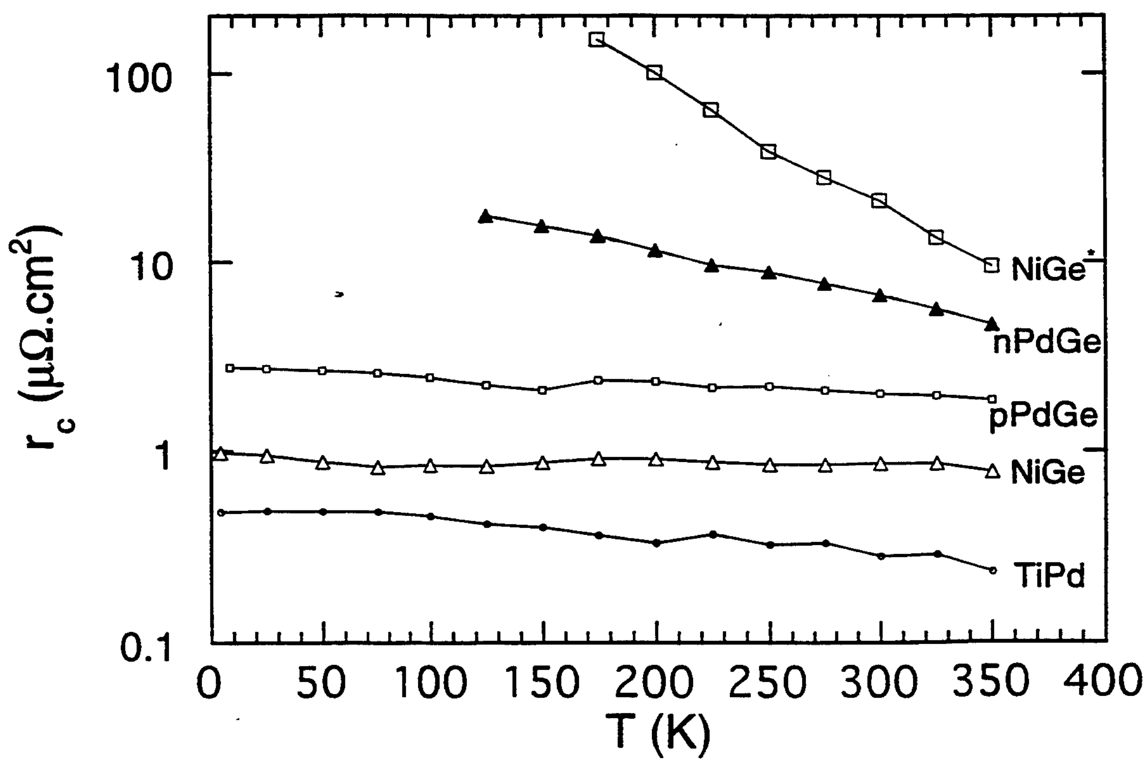
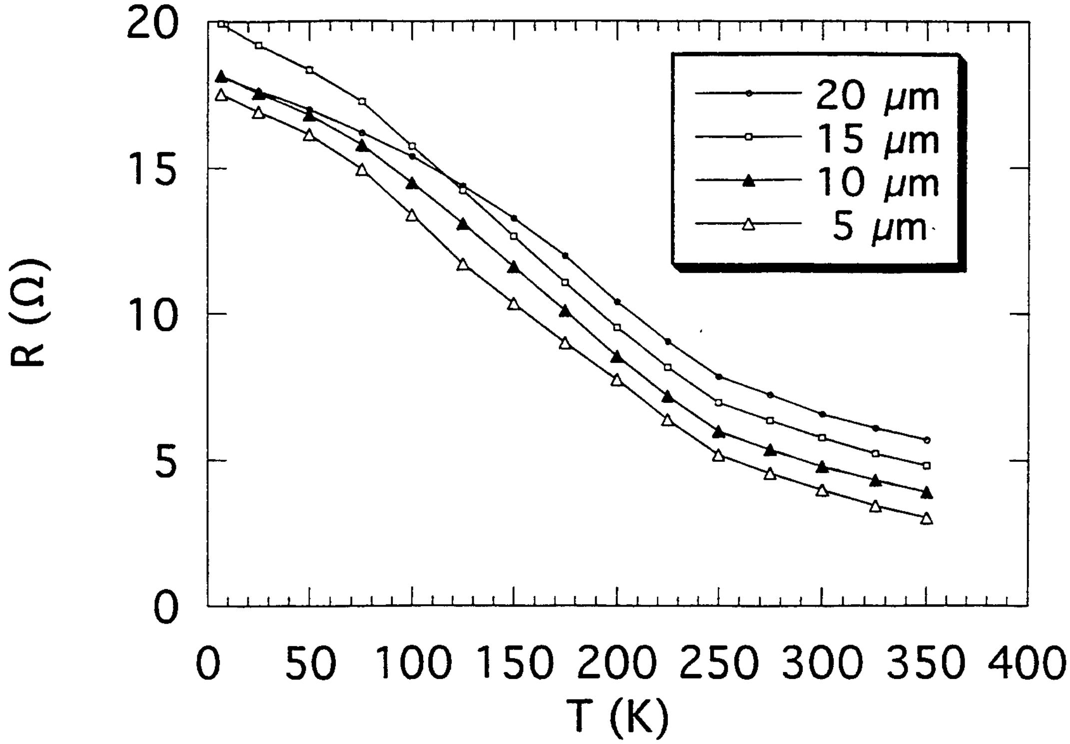
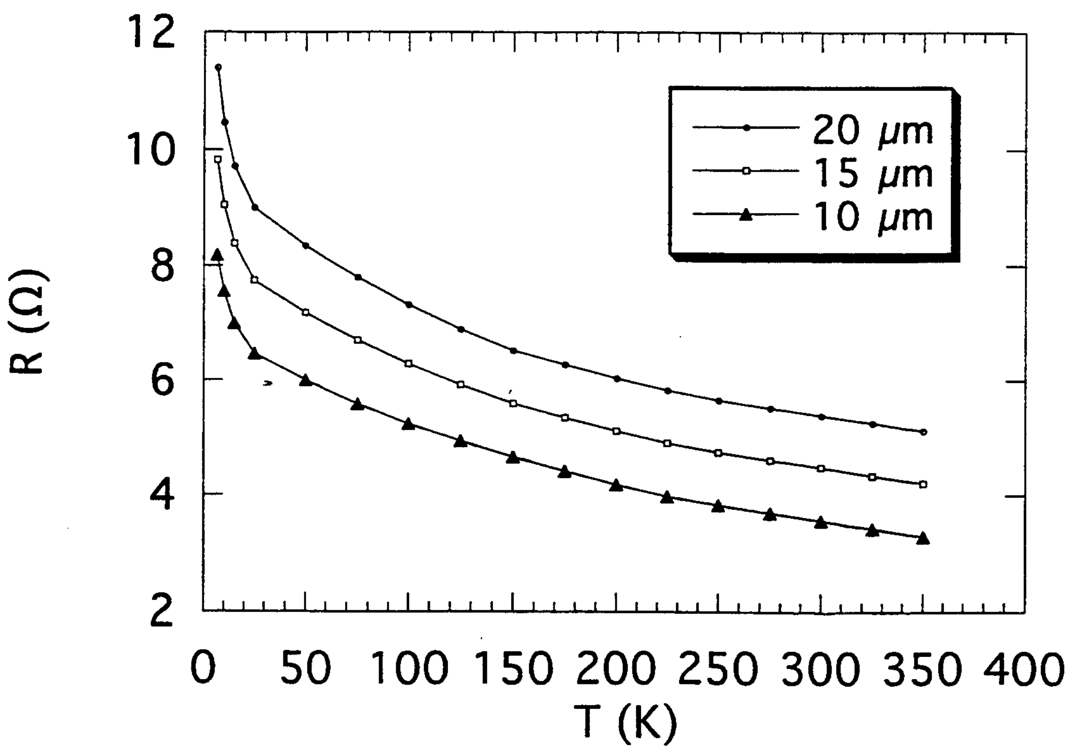


Figure 1. The specific contact resistance of the four different types of contacts that were annealed at 395°C for 90 sec and for the NiGeAu contact annealed at 350°C for 15 sec (*) plotted as a function of the temperature.



(a)



(b)

Figure 2. The resistance between the TLM pads of the (a) NiGeAu contact annealed at 350°C for 15 sec and (b) n-PdGeTiPt contact annealed at 395°C for 90 sec plotted as a function of the temperature

predicted by the field emission (FE) model.[14-16] In this model carriers tunnel directly from the top of the donor band U_F above the bottom of the conduction band into the metal and vice versa, as is shown for n-type material in Fig. 3. This is what one would expect as the semiconductor is very heavily doped, and there is no evidence that the Ti or Pd affects the electrical properties of the junction other than possibly lowering the barrier height a little through the formation of TiAs.[12]

The 350°C/15s p-PdGeTiPt contact behaves in much the same way except that its contact resistance is 4-6 times larger. This can be explained by partial compensation when Ga rapidly out-diffuses into the Pd, and Ge fills in the vacancies left behind. However, it is more difficult to explain the results for the 395°C/90s p-PdGeTiPt contact. Although r_c is lower at room temperature, it increases more rapidly as the temperature decreases, and at 4.2K it is actually larger. One can account for the lower r_c at room temperature by more Ge diffusion into As vacancies, but this should also apply to the measurements at 77 and 4.2K.

The fact that r_c changes more rapidly with the temperature suggests that tunneling occurs by temperature field emission (TFE).[14-16] That is, the carriers are thermally excited to E_m above the bottom of the conduction band before they tunnel. Although the number of carriers that are thermally activated is less than the number at the top of the carrier band, their great-

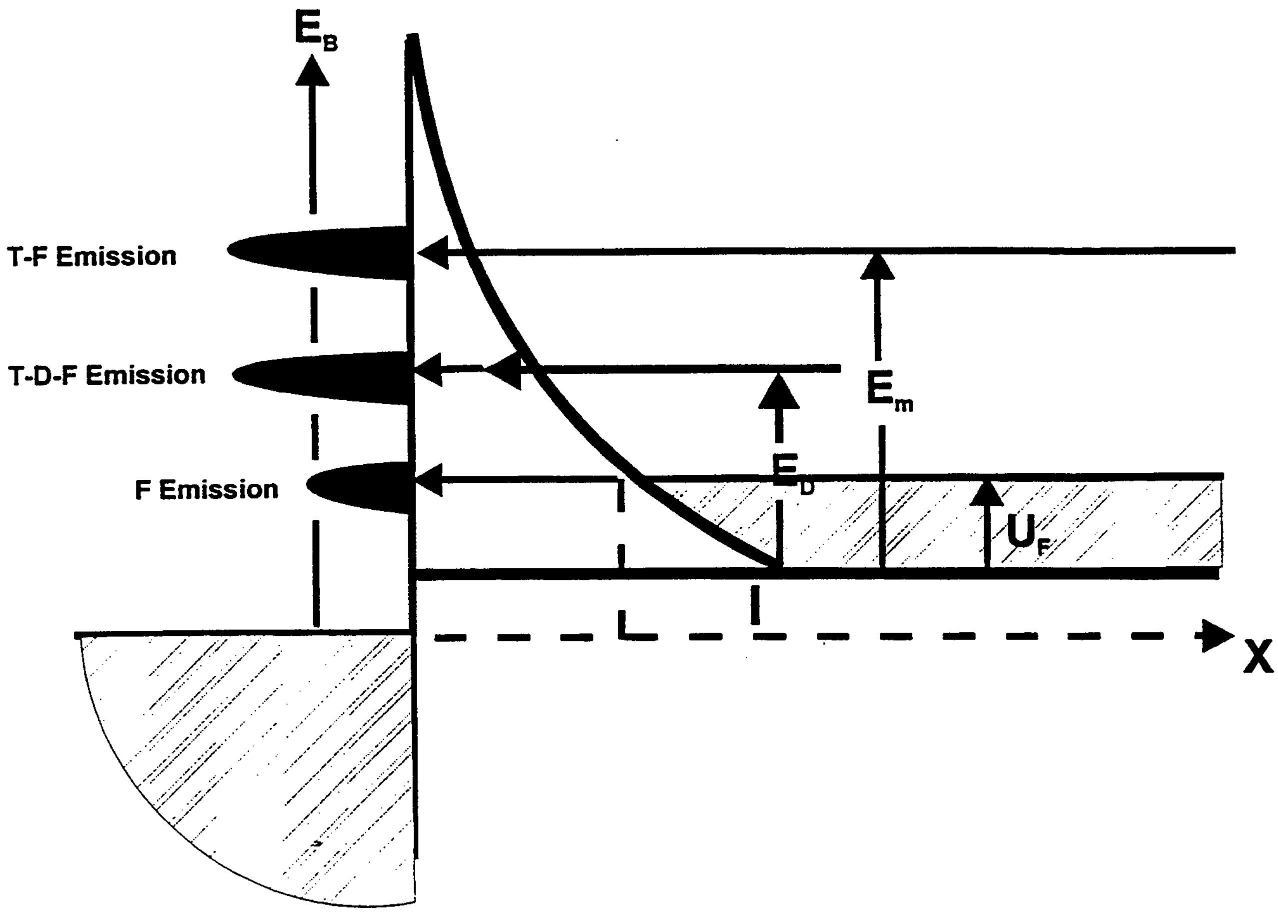


Figure 3. Schematic diagram illustrating field emission, FE, thermal field emission, TFE, and thermal field emission utilizing a deep defect state, TDE.

er tunneling probability through a thinner barrier more than compensates for this. However, TFE cannot be the whole story because the lower room temperature r_C of the 395°C/90s p-PdGeTiPt contact implies that the barrier is thinner at 295K, and the larger 4.2K r_C implies that the barrier is thicker at 4.2K.

An alternative explanation is that conduction is by tunneling of thermally activated carriers through defect states E_D above the bottom of the conduction band (TDE) as is illustrated in Fig. 3. At room temperature there are many more thermally activated species with sufficient energy to tunnel to the defect state. The temperature dependence of TDE is larger than that of TFE because as the number of thermally activated carriers decreases, the energy at which the maximum number of carriers tunnel via TFE slides slowly down the curve of the energy band.

That tunneling can occur via defect states is given more credence by the very large temperature dependence of the 350°/15s n-NiGeAu and 395°C/90s n-PdGeTiPt contacts, and the fact that in most instances they are not Ohmic at 4.2K. The relatively high 295K r_C of the 350°C/15s n-NiGeAu is expected because the annealing temperature is below the 355°C eutectic temperature of Au-Ge making it harder for the Au-Ga alloys to form.[17] However, the contacts were Ohmic suggesting that some sort of field emission occurred. The most probable mechanism is tunneling through defect states associated with the in-diffusion of Au. That Au can in-diffuse even at this relatively low temperature has been documented by SIMS.[10] The large temperature dependence of r_c and the fact that the contact is not Ohmic at the lower temperatures can be attributed to not enough electrons having sufficient thermal energy to tunnel to the defect site(s). Similar arguments can be made for the 395°C/90s n-PdGeTiPt. The large 295K r_c is due to partial compensation by Ge acceptors occupying As sites and/or other Pd induced acceptor states. The large temperature dependence of r_c and the fact that the contact is sometimes not Ohmic at the lower temperatures again can be attributed to defect assisted tunneling.

That the conduction process at Ohmic contacts can be more complicated than either simple field emission or thermal field emission through the depletion layer barrier is also suggested by the gap resistance vs temperature curves for the 350°C/15s n-NiGeAu and 395°C/90s PdGeTiPt contacts. The slope of the former is largest at about 150K and the latter shows a sharp rise below 25K. More studies will have to be performed to understand these properties. They might also shed light on why the 395°C/90s n-NiGeAu appears to have a minimum r_c around 77K.

SUMMARY

It has been shown that properly annealed NiGeAu or PdGeTiPt Ohmic contacts can have low contact resistances at 4.2K. Their resistance is much lower than that determined for 2DEG structures, suggesting that there is a larger resistance at the

GaAs/AlGaAs 2DEG interface. Also, TiPd and properly annealed PdGeTiPt can be used for Ohmic contacts to heavily doped p-GaAs at 4.2K. From the contact resistance vs temperature curves between 4.2 and 350K the conduction mechanism for the p-TiPd and for the 350°C/15s p-PdGeTiPt contact can be described by field emission; the 395°/90s p-PdGeTiPt, 395°C/90s n-NiGeAu, and 350°C/15s n-PdGeTiPt contacts can be explained by thermal field emission. However, there are some idiosyncrasies that can be better explained by tunneling through defect states. The behavior of the 350°C/15s n-NiGeAu and 395°C/90s n-PdGeTiPt contacts can only be explained by tunneling through defect states.

ACKNOWLEDGMENTS

We wish to acknowledge the support of the US Army APEX program and to thank the Defence Research Agency (DRA) of the UK for their help in fabricating the samples.

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