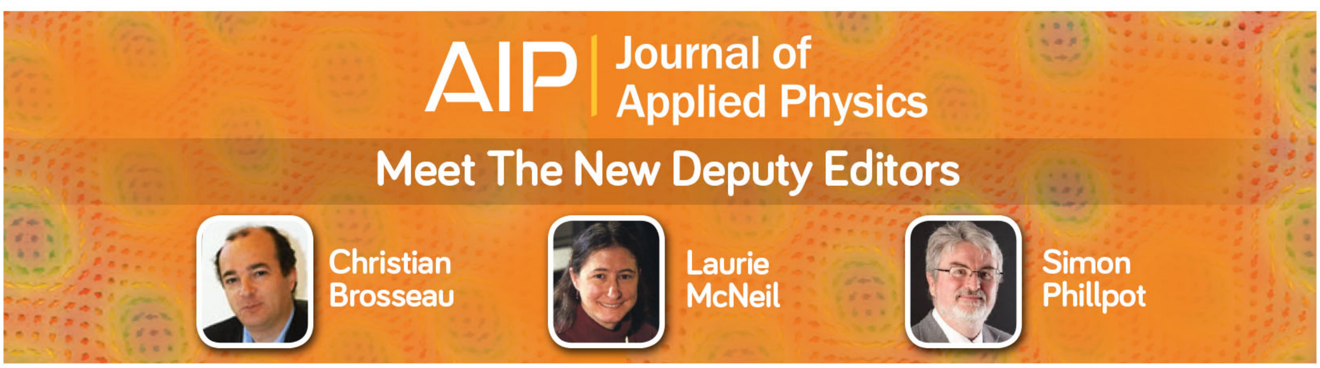
AIP Journal of Applied Physics

Dependence of Andreev reflection and Schottky barriers on GaMnAs/Nb interface treatment

K. F. Eid, D. F. Dahliah, H. A. Abujeib, X. Liu, and J. K. Furdyna

Citation: Journal of Applied Physics **117**, 17E104 (2015); doi: 10.1063/1.4907702
View online: http://dx.doi.org/10.1063/1.4907702
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/117/17?ver=pdfcov
Published by the AIP Publishing



JOURNAL OF APPLIED PHYSICS **117**, 17E104 (2015)

Dependence of Andreev reflection and Schottky barriers on GaMnAs/Nb interface treatment

K. F. Eid,[1,a)] D. F. Dahliah,[1] H. A. Abujeib,[1] X. Liu,[2] and J. K. Furdyna[2]
[1]*Department of Physics, Miami University, Oxford, Ohio 45056, USA*
[2]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*

(Presented 5 November 2014; received 22 September 2014; accepted 20 October 2014; published online 11 February 2015)

We studied the interfacial contact between GaMnAs and superconducting Nb micro-structures both with and without removing the native GaMnAs surface oxide. Our results show that a strong Schottky barrier forms at the interface when the oxide layer is left between Nb and GaMnAs. This barrier can be confused for Andreev Reflection and erroneously used to extract spin polarization. A simple acid etch is shown to remove the oxide film, thus decreasing the interface resistance, removing the Schottky barrier, and causing a clear Andreev reflection effect. One key recommendation for point contact Andreev reflection studies is to push the tip hard enough into contact and verify that the total resistance is not too high. © *2015 AIP Publishing LLC*.
[http://dx.doi.org/10.1063/1.4907702]

I. INTRODUCTION

Andreev reflection (AR) spectroscopy offers a simple and powerful tool to study spin polarization in ferromagnetic materials. The conductance at the interface between a superconductor and a non-ferromagnetic, non-superconducting material (N) is enhanced for voltages below the superconducting energy gap due to the formation of Cooper pairs.[1] If a ferromagnetic (F) material is placed in contact with the superconductor; then, the Cooper pair formation is suppressed. The magnitude of the suppression depends on the severity of the shortage of minority-spin charge carriers (i.e., on the degree of spin polarization), which leads to a reduction in the conductance of the interface. So, the conductance inside the superconducting energy gap is directly dependent on the spin polarization in (F), allowing the utilization of AR spectroscopy to estimate spin polarization.[2,3] This technique has been successfully used to extract the spin polarization in many ferromagnetic materials, where the analysis typically uses a modified BTK model to account for the reduced minority spin densities.[4–6]

The analysis of AR data is not straight forward, since several factors have to be taken into account, like the z-factor, the temperature, and the spin scattering, in addition to the spin polarization.[7] Recent papers have also pointed out to the significant effect of the spin-independent resistance contribution from the bulk of the ferromagnetic film and the spreading resistance.[8–10] AR measurements cannot discriminate between these spin-independent resistance contributions and the true AR process occurring at the interface.

AR spectroscopy measurements have also been used to find the spin polarization of GaMnAs,[11] yet they proved to be difficult to achieve and to interpret, leading to disagreement on the value of spin polarization and on the origin of the broadening of the superconducting energy gap.[12–15] Some papers in literature attributed this to the high resistivity of GaMnAs causing spectra broadening.[8,9] This is supported by extremely high resistance values from point contact Andreev reflection (PCAR) measurements and the AR spectra that are significantly wider than the superconducting gap. It is important in this context to vary the conditions of the GaMnAs/Nb interface and study their effect on the charge transport properties of these bilayers. Such a detailed understanding of the transport properties at the interface helps understand the widespread disagreement in the AR spectroscopy results on GaMnAs.

II. EXPERIMENTAL

We use standard photolithography to fabricate Nb micro-structures on GaMnAs films. These samples were prepared using Molecular Beam Epitaxy (MBE) and then photolithography followed by high-vacuum Nb sputtering and lift-off to pattern micro-structures as shown in the cartoon in Fig. 1(a). The sputtered Nb film covers the entire GaMnAs surface but has gaps in the Nb isolating some Nb micro-sized islands from the surrounding Nb covering the GaMnAs film. The width of the gaps ranges from 2 μm to 80 μm and the radius of the middle island is 300 μm.[16,17] The resistance

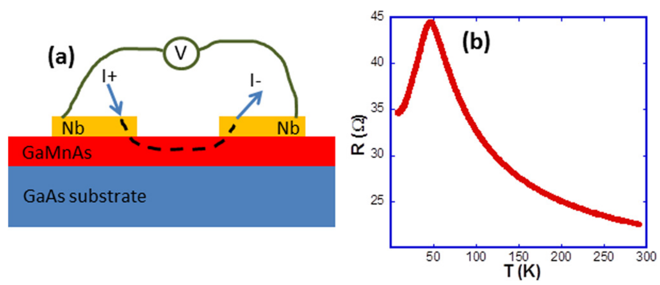


FIG. 1. (a) Cartoon showing Nb microstructures on the GaMnAs films and the four-probe measurement geometry. (b) The resistance between two microstructures is that of the two interfaces plus the bulk GaMnAs resistance, since Nb is superconducting.

[a)]Author to whom correspondence should be addressed. Electronic mail: eidkf@muohio.edu between any of the Nb circular islands and the outside Nb is directly proportional to the ring width, so if we plot the resistance as a function of gap width we get a straight line, whose slope gives the GaMnAs resistivity and y-intercept is twice the contact resistance.

Two types of samples were prepared from the same GaMnAs substrate: In the first type, the Nb film was deposited directly on GaMnAs with the native oxide left in place. This is meant to be just like in a PCAR measurement, where the superconducting tip is brought into contact with the, typically untreated, semiconductor surface. GaMnAs is known to develop a native oxide film of thickness about 1 nm within hours of its exposure to ambient oxygen.[18] In the second type of samples, the native oxide film on GaMnAs was stripped off immediately before the sample was introduced in the vacuum chamber by immersing it in HCl acid for 20 s. Since the re-growth of the oxide film takes several minutes, to hours, this immediate transfer of the sample into the vacuum chamber after acid etching guarantees a relatively clean surface. The Curie temperature of the as-grown GaMnAs films is around 45 K as seen from Fig. 1(b), which shows the resistance as a function of temperature for one of the microstructures. The resistance shows a clear peak as is typical for GaMnAs having a peak around the Curie temperature. It should be noted here that this is the total resistance coming from bulk GaMnAs within the gap area between the two Nb features plus that from the two GaMnAs/Nb interfaces.

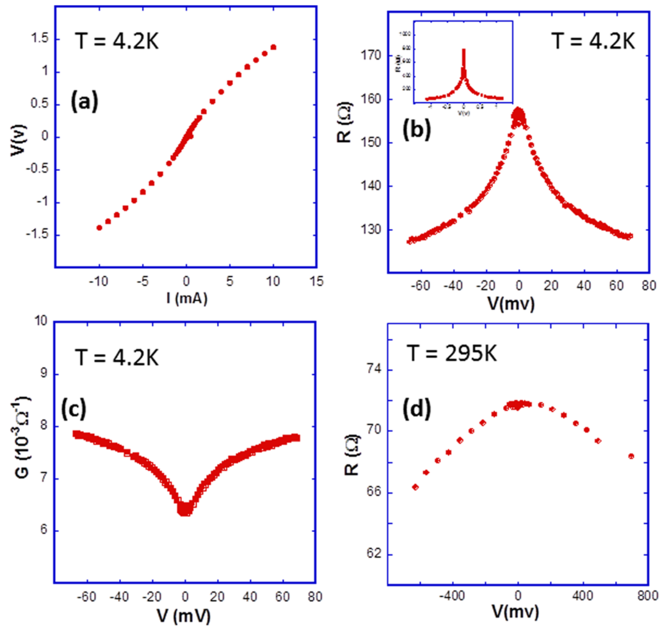


FIG. 2. Transport characteristics at the GaMnAs/native oxide/Nb interface. (a) Non-linear I(V) curve. (b) Resistance drops and slowly saturates with applied voltage, which is indicative of the presence of a Schottky barrier at the interface. The inset shows the R(V) curve for another sample and for a much wider range of voltages. (c) The conductance increases slowly with increasing the applied voltage. (d) The variation of resistance with applied voltage at room temperature is clear evidence that there is a Schottky barrier at the interface.

III. RESULTS AND ANALYSIS

Figures 2(a) and 2(b) show the current-voltage, I(V), and resistance R(V) curves for a sample with the native oxide left at the interface. The sample has a significant drop in resistance (or rise in conductance) as the applied voltage is increased. The inset in Fig. 2(b) shows the R(V) curve for another sample in a wider voltage range. The shape of the R(V) curve is a hallmark of a Schottky barrier, where there is an exponential drop in resistance with increasing the applied voltage. The symmetric nature of the curve is due to having two opposite Schottky barriers in the sample: If current is sent from an inner Nb circular island to the outer Nb structure, then it flows in the superconductor, encounters the first Schottky barrier as it flows into the GaMnAs at the outer edge of the disk, flows into the GaMnAs area between the two Nb features, and finally encounters the second Schottky barrier as it flows from GaMnAs into the outer Nb structure. So, the current will always flow from the semiconductor (GaMnAs) into the superconductor at one interface and from the superconductor to GaMnAs at the second interface, regardless of the direction of current flow. This leads to the symmetric R(V) curve seen in Fig. 2(b).

One might argue that AR can produce this R(V) behavior (or the resulting conductance, G(V), curve, which is shown in Fig. 2(c)). The resistance drops with applied voltage, and then saturates slowly, and the saturation happens in relatively low voltages in these samples. At first, this slow saturation (and the absence of abrupt jumps in resistance at the superconducting energy gap edges) can be attributed to the AR spectra broadening due to the spreading resistance. In fact, multiple data curves observed by Chiang *et al.* (Ref. 8) look almost identical to Fig. 2(c) and are interpreted as Andreev reflection spectra. Yet, comparing the results with these in Fig. 2(d), one quickly concludes that this peak in resistance has nothing to do with AR and is simply due to the presence of a Schottky barrier at the interface, because it is seen even at room temperature, where Nb is not a superconductor. It is extremely unlikely that there is any resistance variation associated with Andreev effect in these curves. The authors of Ref. 8 measure a very high resistance when using the PCAR technique to study GaMnAs and, consequently, use AR theory to extract the spin polarization of GaMnAs. The high resistance that they observe further suggests that they actually had a Schottky barrier effect rather than Andreev effect.

Figures 3(a) and 3(b) show the I(V) and R(V) curves for a sample with a relatively clean Nb/GaMnAs interface obtained by chemically etching the native oxide film at the surface of GaMnAs. It is seen that the I(V) curve is linear at room temperature and that R is independent of V, indicating the absence of any Schottky barriers. Furthermore, the resistance is much smaller than that found in Fig. 2(b) due to the oxide removal, so this is an Ohmic contact as is usually observed for clean contacts with very-highly doped semiconductors.[16]

Clear Andreev reflection spectra are seen in Figs. 3(c) and 3(d), which are taken at 4.2 K. Unlike the similar curves taken when there is an oxide layer at the interface (i.e., in Figs. 2(b) and 2(c)), these curves now show clear superconducting energy gaps that are symmetric around the origin. This clearly demonstrates that the observed curves are

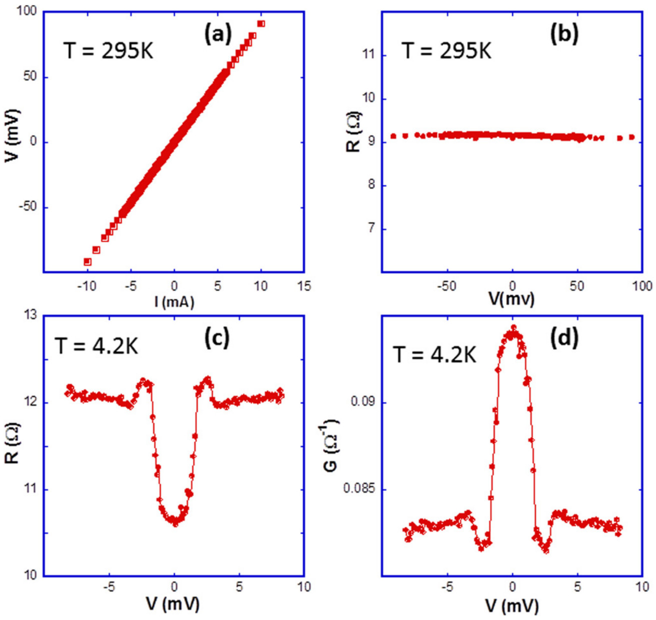


FIG. 3. Transport in micro-structures with clean GaMnAs/Nb interface. (a) Linear I-V curve at room temperature. (b) The resistance is independent of voltage at room temperature (i.e., Ohmic behavior of the interface). (c) Clear Andreev reflection spectroscopy at 4.2 K. (d) The conductance at 4.2 K shows a typical Andreev reflection curve. The lines are guides to the eye.

indeed due to Andreev effect rather than any possible Schottky barrier. Fig. 3(c) displays the total resistance of one microstructure, due to both the bulk GaMnAs and GaMnAs/Nb interface contributions, while Fig. 3(d) shows the total conductance G (V), which is the quantity usually plotted and analyzed in AR studies.[16] The lines in Figs. 3(c) and 3(d) are not actual fits but only guides to the eye. It is clear, though, that the spin polarization that can be extracted from these curves is low, since the resistance inside the superconducting energy gap is larger than outside of it. We estimate the contact resistance to be $R_C \cong 4\ \Omega$ and the spin polarization to be less than 0.4. This is most likely due to the presence of a magnetically dead layer in the GaMnAs closest to Nb and to the presence of strong spin-flip scattering as the charge carriers tunnel through the interface. The presence of such a magnetically dead layer is consistent with our contact resistance studies in GaMnAs/Cu bilayers[16] and is most likely due to a thin depletion zone at the metal/semiconductor interface.

Comparing the curves in Fig. 2 with these in Fig. 3, it is seen that a Schottky barrier can lead to a conductance curve that looks slightly similar to that due to Andreev effect, yet it shows no abrupt jumps in conductance at the superconducting energy gap of Nb and, most importantly has a significantly higher resistance. This behavior was consistently seen in several samples of both kinds. Such lack of clear gap edge and presence of high resistance should be strong warning signs that one is actually having a Schottky barrier rather than Andreev reflection curve. So, it is extremely important to push the superconducting tip enough into the ferromagnetic surface until the resistance becomes low in PCAR studies, even in high-resistivity materials. This insures that one has established a good contact with the actual GaMnAs (or other material), rather than the top oxidized layer.

IV. CONCLUSIONS

In conclusion, we studied the contact between GaMnAs and superconducting Nb. Our results point to the crucial role of the native oxide layer in producing a pronounced Schottky barrier and suppressing any AR effect. The sharp superconducting tip should be pressed hard enough to break through the oxide film and establish a good contact with the actual GaMnAs in order to get useful AR spectroscopy results.

ACKNOWLEDGMENTS

This research was supported in part through NSF Grant No. DMR1400432.

[1]G. E. Blonder, M. Tinkham, and T. M. Klapwijk, Phys. Rev. B **25**, 4515 (1982).
[2]R. J. Soulen, J. M. Byers, M. S. Osofsky, B. Nadgorny, T. Ambrose, S. F. Cheng, P. R. Broussard, C. T. Tanaka, J. Nowak, J. S. Moodera, A. Barry, and J. M. D. Coey, Science **282**, 85 (1998).
[3]I. I. Mazin, A. A. Golubov, and B. Nadgorny, J. Appl. Phys. **89**, 7576 (2001).
[4]Y. Ji, G. J. Strijkers, F. Y. Yang, C. L. Chien, J. M. Byers, A. Anguelouch, G. Xiao, and A. Gupta, Phys. Rev. Lett. **86**, 5585 (2001).
[5]V. N. Krivoruchko, A. I. D'yachenko, and V. Y. Tarenkov, Low Temp. Phys. **39**, 211 (2013).
[6]R. P. Panguluri, T. S. Santos, E. Negusse, J. Dvorak, Y. Idzerda, J. S. Moodera, and B. Nadgorny, Phys. Rev. B **78**, 125307 (2008).
[7]G. T. Woods, R. J. Soulen, Jr., I. Mazin, B. Nadgorny, M. S. Osofsky, J. Sanders, H. Srikanth, W. F. Egelhoff, and R. Datla, Phys. Rev. B **70**, 054416 (2004).
[8]T. W. Chiang, Y. H. Chiu, S. Y. Huang, S. F. Lee, J. J. Liang, H. Jaffres, J. M. George, and A. Lemaitre, J. Appl. Phys. **105**, 07C507 (2009).
[9]T. Y. Chen, S. X. Huang, and C. L. Chien, Phys. Rev. B **81**, 214444 (2010).
[10]J. Wei, G. Sheet, and V. Chandrasekhar, Appl. Phys. Lett. **97**, 062507 (2010).
[11]I. Žutić and S. Das Sarma, Phys. Rev. B **60**, R16322 (1999).
[12]J. G. Braden, J. S. Parker, P. Xiong, S. H. Chun, and N. Samarth, Phys. Rev. Lett. **91**, 056602 (2003).
[13]C. H. Kant, A. T. Filip, H. J. M. Swagten, and W. J. M. de Jonge, Phys. Rev. Lett. **93**, 169703 (2004).
[14]R. P. Panguluri, K. C. Ku, T. Wojtowicz, X. Liu, J. K. Furdyna, Y. B. Lyanda-Geller, N. Samarth, and B. Nadgorny, Phys. Rev. B **72**, 054510 (2005).
[15]S. Piano, R. Grein, C. J. Mellor, K. Vyborny, R. Campion, M. Wang, M. Eschrig, and B. L. Gallagher, Phys. Rev. B **83**, 081305(R) (2011).
[16]K. F. Eid, B. Paudel, G. Riley, D. Dahliah, X. Liu, and J. K. Furdyna, Appl. Phys. Lett. **100**, 212403 (2012).
[17]K. F. Eid, B. Paudel, N. Opondo, C. Otieno, G. Riley, X. Liu, and J. K. Furdyna, IEEE Trans. Magn. **47**, 2636 (2011).
[18]M. R. Vilar, J. El Beghdadi, F. Debontridder, R. Artzi, R. Naaman, A. M. Ferraria, and A. M. Botelho do Rego, Surf. Interface Anal. **37**, 673 (2005).