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Low temperature current transport of Sn-GaAs contacts

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We measure low temperature current transport properties of superconducting Sn contacts to p^+-GaAs. For contacts alloyed at 450 °C, the current-voltage characteristics show a strong dependence on alloying time. The critical temperature of Sn near the superconductor-semiconductor interface decreases from 3.8 to 1.8 K as the alloying time increases from 0 to 120 s. On the other hand, a long-time alloying increases the transparency of the interface. Using the Blonder, Tinkham, and Klapwijk model [Phys. Rev. B **25**, 4515 (1982)], we find that the transmission coefficient of the interface increases from 0.2 to 0.7 by alloying. However, the normal state resistance calculated using the model is much smaller than the experimental value.

There has been considerable interest in superconductor(S)-semiconductor(N) structures because of their potential for three-terminal superconducting devices. SNS weak links using semiconductors such as Si, InAs, and InGaAs have been studied extensively.[1,2] These semiconductors are usually operated in the dirty and diffusive regime due to their short mean free path of carriers. In these structures supercurrents due to the proximity effect were observed. In the clean and ballistic regime several new aspects of supercurrent transport are expected. In this new regime supercurrents are believed to be carried by discrete bound states caused by coherent Andreev reflection.[3] Also, it has been predicted theoretically that the supercurrent through a superconducting point contact in a two-dimensional electron gas (2DEG) increases stepwise if the width of the contact is varied.[4]

A SNS weak link using a 2DEG of GaAs/AlGaAs heterostructure is one of the promising candidates. The high mobility in the 2DEG (typically 1×10^6 cm^2/V s at 4.2 K) results in a long mean free path $l_e \approx 10$ μm, thus making it easier to produce a device that will operate in the clean and ballistic limit. The 2DEG is formed typically 80 nm below the surface of the GaAs/AlGaAs heterostructure. To have contacts with the 2DEG an alloying process is needed after patterning the contact material. The superconducting material Sn can be used for superconducting contacts to the 2DEG because of the relatively low Schottky barrier to GaAs. Contact to a 2 DEG of GaAs/AlGaAs was first made by Ivanov *et al.*[5] using Sn/In, and recently reported by Lenssen *et al.*[6] using Sn/Ti. For alloyed contacts two questions need to be answered. First, is Sn still a superconductor near the interface of Sn and the semiconductors? Second, how does the alloying process influence the current-voltage (I-V) characteristics of the interface?

To study the effects of alloying on the interface, we measure the low temperature transport properties of several Sn-GaAs contacts. The contacts are alloyed at a constant temperature but for different times. To our knowledge no such experiments have been reported before.

The GaAs used is (100) oriented and p type with high Zn dopant concentration of 2×10^{18} cm^{-3}. It has a resistivity of 0.02 Ω cm at room temperature. After the wafer is cleaned in a solution H_2O:NH_4OH = 25:1 for 2 min, a layer of 300 nm Sn is deposited by e-gun evaporation at a pressure of 1×10^{-6} Torr. Without breaking the vacuum a 200 nm Nb and a 300 nm Au layer are evaporated on top of the Sn. Nb is used to prevent the "balling-up" effect during alloying. Au is used for bonding. The metal patterns are defined using photolithography and the lift-off technique. In this way, eight Sn contacts, with an area of 0.03 mm^2, are formed on a "chip" in a Hall configuration. Each chip diced from the wafer is alloyed in a furnace in forming gas (10% H_2, 90% N_2) at 450 °C for different times.

We measure electrical characteristics of each individual Sn-GaAs contact using a three-terminal technique. Figure 1 shows typical I-V characteristics of an unalloyed contact, measured at several temperatures. Above 3.7 K the I-V curve is linear, giving a normal state resistance (R_N) of 5.5 Ω. Below 3.7 K the I-V curves are nonlinear. In inset (a) the measured differential resistance R at 1.6 K demonstrates the nonlinearity more clearly. On the curve a strong resistance peak occurs near zero bias, and a minimum appears around 0.9 mV. The latter is a signature of the superconductor energy gap of Sn. The position of this minimum becomes 1.1 mV as temperature increases from 1.6 to 3.1 K. Beyond this voltage the resistance approaches the normal state value. We also measure the differential resistance R_0 of the same contact at zero bias as a function of temperature; the result is presented in inset (b). An increase in resistance around 3.8 K is the onset of superconductivity of Sn. Decreasing the temperature further yields an increase in resistance. However, R_0 does not change rapidly, in contrast to conventional SIN tunneling junctions (I denotes insulator) where it depends on temperature exponentially.[7]

The features we observed are very similar to those re-

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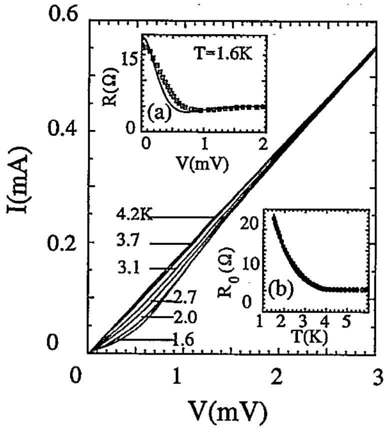

FIG. 1. *I*-*V* characteristics of an unalloyed Sn/GaAs contact at a number of temperatures. The inset (a) shows the differential resistance *R* vs bias voltage, measured at 1.6 K. The inset (b) shows the differential resistance R_0 at zero bias vs temperature. In the insets the points represent experimental data and the curves theoretical results calculated using the BTK model.

ported previously in Nb-Si[8] and Nb-GaAs[9] contacts. In these so-called SIN-like junctions usually the Schottky barrier dominates the interface and acts as an insulator. Because of the finite height of the barrier, the interface is relatively transparent. Consequently, some Andreev reflection takes place and weakens the temperature dependence of the resistance. From our data we obtain a critical temperature T_c, which is close to $T_c=3.7$ K of bulk Sn. The energy inferred by the minimum in the resistance does not coincide with the superconductor energy gap $\Delta(\Delta=0.57$ meV). As found in SIN-like junctions,[8,10] this minimum is not a good measure of Δ.

Figure 2 shows the differential resistance vs voltage bias at 1.6 K for five Sn-GaAs contacts, which are alloyed at 450 °C for 0, 15, 30, 45, and 120 s, respectively. This alloying temperature is commonly used for ohmic contacts to a 2DEG of GaAs/AlGaAs heterostructures. We find that times, longer than 30 s, are needed to realize good contacts to the 2DEG. By long-time alloying the resistance peaks near zero bias are suppressed, and the voltage corresponding to the minimum in the resistance decreases. The inset of Fig. 2 shows the normal state resistance as a function of alloying time. The value of R_N decreases from 5.5 to 0.21 Ω after 120 s alloying. These correspond to the specific contact resistances 1.7×10^{-3} and 6.3×10^{-5} Ω cm^2, respectively. In another experiment the differential resistances of the contacts zero bias are measured as a function of temperature. Figure 3 shows the results and the inset gives a magnified plot near T_c. Generally speaking the temperature dependence of alloyed contacts is similar to that of unalloyed contacts. However, due to longer alloying, the temperature dependence becomes weaker. On the other hand, due to alloying T_c decreases from 3.8 to 1.8 K after 120 s alloying. This is consistent with the smaller energy gap of the material after longer alloying as can be seen in Fig. 2.

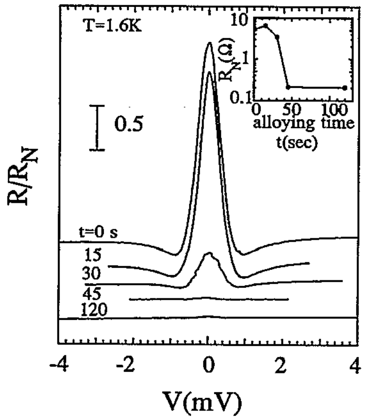

FIG. 2. The reduced differential resistance as a function of bias for several Sn/GaAs contacts alloyed at 450 °C for different times. The tunneling behavior characterized by peaks in the resistance is suppressed by long-time alloying. For clarity there are offsets in the *Y* direction. The inset shows the normal state resistance R_N as a function of alloying time.

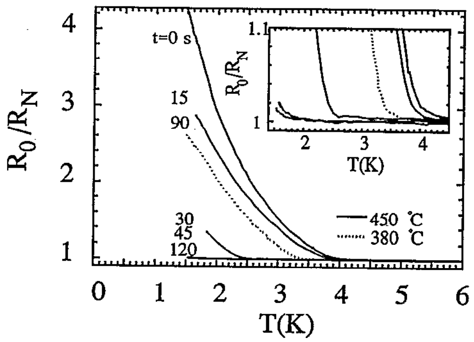

FIG. 3. The reduced differential resistance at zero bias vs temperature for the same contacts as in Fig. 2. For comparison, the result of a contact alloyed at 380 °C is also shown by the dashed line. The inset shows a magnified plot of the temperature dependence of resistance near T_c.

We also measure the temperature dependence of the resistance of a contact alloyed at 380 °C for 90 s. The result is also shown in Fig. 3 by the dashed line. Note that, at the lower alloying temperature, T_c of Sn has also changed to 3.4 K.

We analyze our experimental data using the Blonder, Tinkham, and Klapwijk (BTK) model[11] for current transport. In this model the potential barrier between S and N, in our case the Schottky barrier and a residual native oxide layer, is modeled as a delta function potential. A dimensionless barrier strength *Z*, giving the normal state transmission coefficient by $T_N=(1+Z^2)^{-1}$, is introduced to describe Andreev reflection coefficient $A(E)$ and normal reflection $B(E)$. According to the model the voltage and temperature dependence of the differential resistance is given by

$$R(V,T)=\frac{R_N}{1+Z^2}\left[\int_{-\infty}^{\infty}\left(-\frac{\partial f_0}{\partial E}\right)[1+A(E)-B(E)]dE\right]^{-1}, \quad (1)$$

where f_0 is the Fermi distribution function. Although the BTK model assumes a point-contact geometry of the SIN-

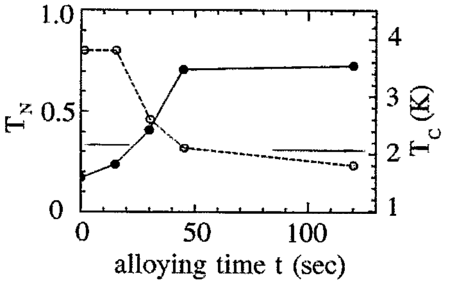

FIG. 4. The transmission coefficient T_N given by $(1+Z^2)^{-1}$ and the critical temperature T_c of Sn near the interface as a function of alloying time. Lines are free interpolations to guide the eye.

like junction, it has been successfully applied to planar Nb-Si[12] and coplanar Nb-InGaAs[13] structures.

We fit this equation to our data of the unalloyed contact, taking R_N from the experiment and using the Z value as a fitting parameter. The fitting results are shown in the insets of Fig. 1. The overall shape of the voltage [inset (a) of Fig. 1] or temperature [inset (b)] dependence of the differential resistance is well reproduced. Fitting to the voltage dependent measurement yields roughly the same Z value ($Z=1.9$) as fitting to the zero bias, temperature dependent measurement. Therefore, we conclude that the BTK model can describe our data reasonably well. To obtain Z values of all contacts we do not use this full equation because of the limitation of the temperature range for contacts alloyed for a longer time. Instead we calculate the Z values using a simplified expression derived from Eq. (1); $R_0(T\rightarrow 0)/R_N=(1+2Z^2)^2/2(1+Z^2)$. Experimental values of R_0/R_N are estimated by extrapolating the curves in Fig. 3 to $T=0$. In this way the transmission coefficient T_N as a function of alloying time, as shown in Fig. 4, is calculated from the Z values. As one can see, one of the effects of alloying is to increase the transparency from 0.2 to 0.7. Another effect, as also shown in Fig. 4, is to reduce the T_c of Sn near the interface.

The increase of the transparency due to alloying can be explained by taking the interdiffusion of Sn and GaAs near the interface into account. Sn diffuses into the semiconductor while Ga, As, and Zn (used as dopant) diffuse in the opposite direction. Consequently, a layer of Sn-rich GaAs at the interface is formed and thus the Schottky barrier strength decreases. The mechanism of reducing the T_c of Sn is still not clear. It may be due to the Sn near the interface containing an amount of Ga, As, and Zn.

Finally we compare R_N values given by the BTK model with the experimental values. Having known the coefficient T_N and carrier concentration, R_N values of 2×10^{-5} Ω for $T_N=0.2$ and 7×10^{-6} Ω for $T_N=0.7$ are calculated using the model. They are about 10^{-4} times smaller than the experimental values. This discrepancy suggests that only a very small part of the interface has the high transparency, thus reducing the effective contact area. Such an assumption is also needed to explain similar results for the Nb-Si structures.[12] There are two possible explanations for this effect. First, because of the high doping level in the GaAs, the Schottky barrier thickness (~20 nm) is comparable with the typical distance of the ionized centers (8 nm). Therefore, a homogeneous barrier model is no longer valid and the barrier strength fluctuates laterally. Second, the alloying may cause spikes in the contacts, where the transparency can be higher than in other region. This explanation might apply to the alloyed contacts but not to the unalloyed case.

In summary, we have measured *I-V* characteristics of Sn-GaAs contacts alloyed at a fixed temperature for different times. The data demonstrate a clear-cut dependence of electrical properties of the contacts on the alloying time. The data also confirm the superconductivity of Sn near the interface. A long alloying time increases the transparency of the interface, which suggests the use of Sn for SNS weak links in a 2DEG GaAs/AlGaAs heterostructures. Unfortunately it also induces a reduction in T_c of Sn near the interface.

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