Ultra-high-ohmic microstripline resistors for Coulomb blockade devices

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Abstract

In this paper, we report on the fabrication and low-temperature characterization of ultra-high-ohmic microstripline resistors made of a thin film of weakly oxidized titanium. Nearly linear voltage–current characteristics were measured at temperatures down to \( T \sim 20 \text{ mK} \) for films with sheet resistivities as high as \( \sim 7 \times 10^4 \) \( \Omega \text{cm} \), i.e. about an order of magnitude higher than our previous findings for weakly oxidized Cr. Our analysis indicates that such an improvement can help to create an advantageous high-impedance environment for different Coulomb blockade devices. Further properties of the Ti film addressed in this work show the promise of low-noise behavior of the resistors when applied in different realizations of the quantum standard of current.

(Some figures may appear in colour only in the online journal)

1. Introduction

The experimental observation and electronic applications of quantum tunneling phenomena, in many cases, require efficient decoupling of the tunneling system from the environmental degrees of freedom responsible for dissipation [1, 2]. This implies, for practical devices, that low-noise operation should be possible for tunneling systems embedded into DC biasing circuitry with an effective output impedance \( \text{Re}\{Z(\omega)\} \gg R_Q \equiv \hbar/4e^2 \approx 6.45 \text{ k}\Omega \), far exceeding the resistance quantum \( R_Q \) up to the frequency and energy ranges relevant for the particular transport mechanisms [3–5].

For a mesoscopic tunneling system, one of the possibilities of constructing a high-ohmic bias is to co-fabricate it on-chip with an adjoining microstrip of a high resistivity thin-film material. For example, successful realizations of quantized charge transport have been demonstrated in ultrasmall tunnel junctions, see, e.g., [6–10], and superconducting nanowires (operating as quantum phase slip junctions) [11] with the help of weakly oxidized Cr resistors with lengths of a few micrometers and typical cross-sections of \( S \sim 10 \times 100 \text{ nm}^2 \) (thickness \( \times \) linewidth), with resistances per unit length up to \( r \sim 5–10 \text{ k}\Omega \text{ m}^{-1} \).

A detailed analysis, see, e.g., [12], and the experimental data obtained so far [8, 9, 11] indicate, however, a significant shunting effect due to the stray capacitances of the microstrip, typically \( c \approx 60 \text{ aF} \text{ m}^{-1} \) [12], so that for frequencies exceeding the roll-off value

\[
\omega_0 = \frac{r}{2cR_0^2},
\]

the on-chip resistor of a certain length \( l \) and a designated impedance \( Z(0) = R_0 = rl \) must be considered as a distributed RC line rather than as a simple lumped element (see, e.g., [2]). In the high-frequency limit, the impedance of the line decays approximately as the square root of the frequency:

\[
\text{Re}\{Z(\omega)\} \approx \sqrt{\frac{r}{2\omega c}},
\]

dropping below the resistance quantum \( R_Q \), i.e., beyond the high-impedance case, for frequencies above \( \omega_c = \omega_0 \times (R_0/R_Q)^2 \).

Given the expected value of \( R_0 \gg R_Q \) and the value of \( c \) fixed by the microstripline design, equation (1) demonstrates an important role of the unit length resistance \( r \) in developing high-ohmic environments effective over a wide frequency range. Unfortunately, fabricating thinner or more strongly oxidized Cr resistors often results in irreproducible granular films exhibiting a pronounced Coulomb blockade of a net current at low temperatures [13]. In the present work, we report on the resistivity behavior of films of titanium evaporated in the presence of oxygen at low pressure.
choice of Ti is inspired by its relatively high resistivity value, about 40 $\mu\Omega\text{cm}$ [14], while its affinity to oxygen can be utilized to avoid the superconductivity of Ti below the transition temperature $T_c = 0.4$ K, as well as to achieve even higher film resistivity. At low temperature, we demonstrate a linear current-to-voltage dependence for the Ti resistors, with $r \leq 70$ k$\Omega\text{cm}^{-1}$ being about an order of magnitude higher than the corresponding values for the Cr films, making titanium an attractive material choice for resistively-biased Coulomb blockade devices based on both tunnel- and quantum phase slip junctions.

2. Experiment and discussion

The experimental structures, see figure 1, were fabricated using electron-beam lithography and the shadow-evaporation technique [15], which is often implemented for structuring ultrasmall tunnel junctions of Al (see a detailed description of our fabrication routine in [16]). In this technique, a 10 nm thin Ti film was first evaporated from a standard e-gun source at a oblique incidence onto the substrate, followed by a normal-angle evaporation of a thicker film of AuPd to form well-conducting current leads. Because of the well-pronounced gettering property of Ti films, the important parameters of our process were the base chamber pressure, $p < 5 \times 10^{-9}$ mbar, and the evaporation rate of Ti, 0.2 nm s$^{-1}$. In order to increase film resistivity, the deposition of Ti was performed reactively with a small amount of oxygen gas added to the evaporation chamber at a low pressure $P_{O_2} \leq 5 \times 10^{-6}$ mbar. The samples, each one hosting eight different microresistors of a typical microstrip length 1–4 $\mu$m, were tested electrically at room temperature on the day of the evaporation. Brown diamonds and error bars, respectively, represent a sample average and a standard deviation over several different microstrips measured on the day of evaporation. For comparison, we also show the same data obtained after prolonged exposure of the samples to air, at room (RT, red squares and green stars) and at low (LT) temperatures (blue empty circles).

![Figure 1. SEM image of the 10 nm thick titanium resistor contacted by two 40 nm thick leads of AuPd. The structure consists of two metallic replicas (Ti and AuPd) evaporated onto a tilted substrate at two different angles through the same hanging mask. The gate electrode was not used in the present experiment. The evaporated titanium produces a smooth and continuous film, with a grain size below the resolution limit of the SEM (of a few nm). A strong charge build-up effect was observed as a gradual darkening of the Ti lines during the imaging process, indicating, also in this way, the extremely high resistivity of the Ti film.](image1)

![Figure 2. The resistance of Ti film as a function of oxygen pressure during evaporation. Brown diamonds and error bars, respectively, represent a sample average and a standard deviation over several different microstrips measured on the day of evaporation. For comparison, we also show the same data obtained after prolonged exposure of the samples to air, at room (RT, red squares and green stars) and at low (LT) temperatures (blue empty circles).](image2)
where the electron temperature $T_e$ can be calculated by taking into account the Joule power $P$

$$T_e = \left[ \frac{P_{\text{ph}}^5}{\frac{P}{\Sigma \Omega}} \right]^{1/5},$$

(3)

where $P$ is the heat flow from the conductivity electrons to the lattice phonons, $\Sigma$ is the electron–phonon coupling constant, and $\Omega = 0.01 \times 0.1 \times 4 \ \mu m^3$ is the volume of the resistor. We expect the phonon temperature $T_{\text{ph}} = T + K P/\Sigma$ to be close to the substrate temperature $T_e$ due to the typically small values of thermal boundary resistance $K$, namely, $K \times T^3 < 0.001 \ \text{K}^4 \ \text{W}^{-1} \ \text{m}^{-2}$ [23]. Here, $\Lambda = 0.1 \times 4 \ \mu m^2$ is the contact area between the microstrip and the substrate.

An important simplification of our model was made due to the high resistivity of the Ti film giving rise to a strong scattering approximation for conduction electrons on the crystal lattice. In particular, we assumed a fully flat, except for the sharp temperature drops at both ends of the Ti wire. Here we stress that no further consideration is given, in the framework of the present study, regarding the boundary Ti/AuPd, so that $T_e(T_b = 0, T) > T_e$. The assumption resulting supposingly in the sharper and less noisy calculated than measured dips for the lowest values of $T$ in figure 3.

In the calculation, we omit an uncertainty term provided by an additional noise of the sample due to external noise power $P_{\text{noise}}$ (i.e., the voltage fluctuations coming through the leads from the measurement circuitry), so that $P \approx IV_b + P_{\text{noise}}$ and $T_e(V_b = 0, T) > T$, the assumption resulting supposingly in the sharper and less noisy calculated than measured dips for the lowest values of $T$ in figure 3.

Furthermore, at $V_b = 0$ we assumed $T_e = T$ and used the experimental $G^{\exp}$ zero-bias conductance values to establish an empirical calibration relation $G(T_e = T) = G^{exp}(V_b = 0, T)$. Finally, the conductance dips $G(V_b, T)$ shown in figure 3(b) were calculated using the calibration relation $G(T_e)$ and the values $T_e$ obtained from equation (3) for each setting ($V_b, T$).

Our much simplified model still demonstrates a reasonable semi-quantitative agreement with the experiment. In this way, it provides a distinct argument for the thermal origin of the dip, making less probable a presence of unwanted granular Coulomb blockade effects (cf., e.g., the case of partially oxidized Cr films [13] or the anodized Ti films in [26]) and related shot-noise effects. Indirect support of this conclusion also appears in the form of a very low-noise level measured in the resistor in the frequency range around $f = 10 \ \text{Hz}$, typical for the background charge fluctuation phenomenon in single-electron tunneling devices [27]. The noise was found unresolvable against the intrinsic noise level $\delta f \sim 10^{-13} \ \text{A Hz}^{-1/2}$ of the current preamplifier.

Due to the higher attainable values of $r$ in the Ti film, as compared to Cr, and according to equation (1), a roll-off frequency higher by one order of magnitude is now expected for the high-ohmic environmental impedance available for applications. For example, for the hybrid single-electron turnstile [4] with typically $R_0 \sim 100 \ \text{k} \Omega$ [28], the roll-off frequency is $\omega_0 \sim 10^{11} \ \text{s}^{-1}$ and the high-impedance behavior extends up to $\omega_0 \sim 10^{12} \ \text{s}^{-1}$ indicating a remarkably wide energy range, up to $\hbar \omega \sim 1 \ \text{meV}$, where the quantum system is decoupled from the environment, thus making

As a somewhat higher estimated value of $\Sigma$ for high-resistivity Ti is found to be plausible, if compared with those for pure materials (cf., e.g., [21, 22]).

Figure 3. Zero-bias conductance dip as a function of temperature: (a) measured experimentally and (b) calculated with the parameter values $K$ and $\Sigma$ shown in the plot. We note that neither the value of $\Sigma$ nor that of $K$ was found to significantly influence the results of calculation.
the suppression of Cooper-pair-electron (CPE) co-tunneling leakage [4] potentially more efficient. For applications with Bloch oscillations devices [6, 9] and quantum phase slip junctions [11], a narrowing by an order of magnitude for the linewidth of oscillations, $\Gamma \propto T_2/R_0$ [3] and, therefore, substantial improvement of the shape of Shapiro-like current steps at $f = 2ef$ (under microwave irradiation of frequency $f$, in the limit $\Gamma/f \rightarrow 0$) are expected [29].

In conclusion, we reported on ultra-high-ohmic microstripline resistors made of titanium films evaporated reactively in the presence of oxygen. This new material exhibited a sheet resistance of up to 7 k$\Omega$, which is an order of magnitude higher than that of previously used Cr films and is expected to be free of intrinsic Coulomb blockade effects related to film granularity, even at the lowest temperatures of the experiment. Due to the latter fact, a further increase in resistivity seems to be possible without immediate loss of linearity. The obtained parameters—in particular, a considerable improvement in the roll-off frequency—are promising for the application of Ti resistors in different realizations of quantum standards of current. We anticipate also further cryoelectronic applications for the high-ohmic resistors on the base of the moderately oxidized titanium films reported in this paper.

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