Compact chromium oxide thin film resistors for use in nanoscale quantum circuits

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We report on the electrical characterisation of a series of thin chromium oxide films, grown by dc sputtering, to evaluate their suitability for use as on-chip resistors in nanoelectronics. By increasing the level of oxygen doping, the room-temperature sheet resistance of the chromium oxide films was varied from 28 Ω/□ to 32.6 kΩ/□. The variation in resistance with cooling to 4.2 K in liquid helium was investigated; the sheet resistance at 4.2 K varied with composition from 65 Ω/□ to above 20 GΩ/□. All of the films measured displayed ohmic behaviour at all measured temperatures. For on-chip devices for quantum phase-slip measurements using niobium-silicon nanowires, interfaces between niobium-silicon and chromium oxide are required. By characterising the interface contact resistance, we found that a gold intermediate layer is favourable: the specific contact resistivity of chromium-oxide-to-gold interfaces was 0.15 mΩcm², much lower than the value for direct chromium-oxide to niobium-silicon interfaces, 65 mΩcm². We conclude that these chromium oxide films are suitable for use in nanoscale circuits as high-value resistors, with resistivity tunable by oxygen content.

I. INTRODUCTION

Since the 1960s, on-chip thin-film resistors have found applications in integrated circuits [1, 2]. Materials such as NiCr [3, 4], SiCr [5, 6], TaN [7, 8], and TiO [9] have all been used, fabricated by evaporation or sputter deposition. They provide room-temperature sheet resistances ranging from 10 Ω/□ to 2000 Ω/□, but materials to provide higher sheet resistances are less commonly used, with W and Bi [10] being reported for this use. In nanoscale electronic circuits, there is frequently a need for resistive elements which are smaller than the wavelength associated with the frequency of interest. In particular, in coherent quantum circuits there is a need for compact resistors to isolate devices from the environment at frequencies in the GHz range [11]. The isolating resistor must also be sufficiently compact that its resistance is not shorted by the capacitance across the substrate. Such resistors have found applications in the fields of Josephson junctions and nanoscale circuits [12–16]. In order to provide a high-value resistor using standard materials, it is necessary to pattern long (often meandering) paths, thereby leading to an undesirably high shunt capacitance.

A particular example of an application requiring high-value resistors is circuits for exploiting quantum phase-slips. In 2006, Mooij and Nazarov [17] showed a duality between Josephson junctions and a coherent quantum phase-slip (QPS) circuit element — a superconducting nanowire — which implies the potential for a new quantum standard for current. On-chip resistors play an important role in the current-standard QPS circuit, providing a shunt resistance to ensure the overdamped behaviour in which microwave-induced step features are best observed. Work on investigating quantum phase-slips in superconducting nanowires has ensued, including recent microwave spectroscopy measurements, which showed features of coherent QPS origin [18]. The QPS current-standard circuit described by Mooij and Nazarov comprises two resistors on either side of a niobium-silicon nanowire, with a combined series resistance which should exceed a certain value in order to minimise hysteresis in the current-voltage characteristics of this particular circuit. For typical parameters, the series resistance should exceed 60 kΩ.

Chromium oxide is a potential candidate for use as a high-resistance thin-film component [15]. Chromium oxide has a resistance that is tunable through oxygen doping, as well as showing good adhesion to silicon substrates: it is also easy to pattern by chemical etching or lift-off. The electrical and mechanical characteristics of chromium [19, 21], Cr₂O₃ [22], and CrO₂ [23] are all well-documented, due to the numerous applications of these materials in microcoating and magnetic tape manufacture. Less work has focused on amorphous chromium oxide films. Recent studies [24–26] have looked into the mechanical properties of amorphous films and found good hardness and resistance to wear, but the electrical properties of the films are less well-documented. The films are non-magnetic and therefore suitable for use in a circuit with superconducting elements in close proximity. In the past, thin, weakly oxidised Cr resistors with a sheet resistance up to 800 Ω/□ have been employed successfully to provide high resistance [15]; however, the small widths and long lengths necessary to create higher-value resistors in materials such as weakly oxidised chromium or NiCr can be more difficult to fabricate, in addition to the issue of parasitic capacitances. Strongly oxidised chromium oxide films have the advantage of a larger sheet resistance, meaning a high-resistance structure can be more compact. In this paper, the electrical properties of chromium oxide films are investigated in detail. We report on the fabrication of thin-film chromium oxide resistors by sputter deposition, and investigate their structural and electrical properties.

It is also important to control the interfaces which thin-film resistors make to other materials. When two materials meet, there will usually be imperfect contact between them. Impurities, unevenness in each surface and the
mismatch of lattice structures will cause voids and defects at the surface of the two materials, which will lead to an electrical interface resistance \[27\]. Minimising this contact resistance is one of the main practical challenges in fabricating multi-layered on-chip circuits. We have therefore investigated interfaces between chromium oxide and other materials. We report on tests of niobium-silicon-to-chromium-oxide interfaces; these are relevant in the preparation of these resistors for use in a quantum phase-slip circuit in which the thin-film resistors must be electrically connected to niobium-silicon nanowires fabricated by multi-stage electron-beam lithography. We also present results of tests of chromium oxide-to-gold interfaces.

II. COMPOSITION

A. Fabrication

A series of chromium oxide films was created, using a broad range of oxygen dopant levels. The chromium oxide films were deposited on p-doped silicon by dc-magnetron sputtering in an argon and oxygen atmosphere, using a 3" Cr target with a 500 W sputter power for ten minutes with a three-minute pre-sputter. The target-to-substrate distance was 18 cm. The argon gas pressure was 5 mTorr. The film thicknesses, measured by a DektakXT surface profiler, were all in the range 179 nm for growth in pure argon to 246 nm for growth with an oxygen partial pressure of 0.7 mTorr, implying deposition rates from 17.9 nm/min to 24.6 nm/min.

B. Structure

Wavelength-dispersive spectroscopy (WDS) in a scanning electron microscope was used to determine the composition of the films grown. Fig. 1 shows the variation of the oxygen-to-chromium mass ratio in the film with the O\(_2\) partial pressure used during sputter deposition. There is a gradual increase in the proportion of oxygen in the film as the pressure of oxygen introduced into the argon gas in the sputterer is increased. There is oxygen present in the film even if no oxygen is added whilst sputtering. This is likely due to oxidation of the surface of the film after removal from the chamber or the influence of residual oxygen in the chamber during growth.

X-ray diffraction was used to investigate the structure of the films. All of the films from Fig. 1 were measured and all were found to be amorphous, with only substrate peaks visible in all measurements. This shows that the magnetic phases of chromium oxide, which could cause suppression of superconductivity in adjacent nanowires, were not present in these films.

III. RESISTANCE MEASUREMENTS

A. Variation in room-temperature resistance with oxygen partial pressure

Four-point electrical transport measurements were performed at room temperature to determine the sheet resistance of the films. A linear contact configuration was used and the measurement was made immediately after removing the sample from the sputterer vacuum chamber.

![Figure 1: Variation of the thickness of material, after a ten minute sputter time, with the oxygen partial pressure. (Lower) Dependence of the oxygen-to-chromium mass ratio in the film (as measured by WDS) on the O\(_2\) partial pressure during growth. An argon gas partial pressure of 5 mTorr was used for all samples.](image1)

![Figure 2: Variation of room-temperature sheet resistance of chromium oxide films with the oxygen-to-chromium mass ratio for the same samples as shown in Fig. 1.](image2)
Fig. 2 shows the variation of room-temperature sheet resistance of the chromium oxide films (the same samples as shown in Fig. 1) with the oxygen-to-chromium mass ratio \[29\]. There is a steep increase in room-temperature sheet resistance as the oxygen incorporation increases, corresponding to a departure from standard metallic conduction. The samples with O/Cr mass ratios of greater than 0.45 are not shown, as their resistances were higher than the measurement range (100 kΩ) of the particular equipment employed.

**B. Variation of resistance with temperature**

In order to measure the resistance of the films as a function of temperature, bonded aluminium wires were used to make contact to the films at four points, spaced by approximately 1 mm, in a linear configuration and the resistance was measured by means of a four-point technique. At room temperature, conduction was ohmic in the measured range of currents, up to 200 µA. The samples were cooled to 4.2 K in liquid helium, and the variation of the resistance of the films with temperature during cooling was measured, using a dc bias current of 10 µA for all films. Conduction remained ohmic at 4.2K for all measured films.

**FIG. 3:** Variation with temperature of measured four-point resistance of the chromium oxide films of varying composition. Labels denote the oxygen-to-chromium mass ratios of the film, as determined by WDS. Lines in gold denote fits to a variable-range hopping model. Films were biased at 10 µA and cooled to 4.2 K. Small jumps in the data are artefacts associated with thermal lag during the measurement. (Inset): IV curve of 0.41 O/Cr mass ratio film at 4.2 K demonstrating ohmic behaviour.

Fig. 3 shows the varied variation of room-temperature sheet resistance with temperature for chromium oxide films of varying composition. The data has been normalised with respect to the resistance at 100 K; in the temperature range shown, conduction through the substrate is negligible. The graph shows that oxygen incorporation has a significant effect on the variation of resistance of the films with temperature, and there is a large variation between the films in the value of low-temperature resistance. The films become more resistive for increasing oxygen concentration. The sheet resistance at 4.2 K was obtained from the measured resistance by means of a standard transformation for the films \[28\] and is shown in Table 1. The 0.41 mass ratio film reaches a maximum sheet resistance greater than 20 GΩ at 4.2 K. More precise measurement of the resistance and IV characteristics at low temperature were not possible for this film because its resistance approached the input impedance of the measurement equipment.

The data shown in Fig. 3 have been fitted to a variable-range hopping form, \( R = R_0 \exp(T_0/T)^n \), where \( T_0 \) is the localisation temperature. For Mott variable-range hopping (VRH), \( n = (d + 1) \) in d dimensions; for Efros–Shklovskii VRH, appropriate for stronger electron-electron interactions, \( n = 1/2 \) \[30\]. This functional form provides a good fit to the data for the films with higher oxygen content, as shown in Table 1. The fitted value of \( n \) varies with the oxygen concentration; it is consistent with 3-D Mott VRH for the 0.37 O/Cr film and Efros–Shklovskii VRH for the 0.41 O/Cr film. The crossover from Mott VRH to Efros–Shklovskii VRH with increasing oxygen content is in line with expectations that electron-electron interactions become increasingly important in the most resistive films. The values of \( T_0 \) were found to be of the order of those found in other materials that exhibit Efros–Shklovskii VRH \[31, 32\]. \( T_0 \) is related to the localisation length \( \xi \) via the equation \( T_0 = e^2 \beta/k_B k \xi \) where \( \beta \) is a numerical constant, \( k_B \) is the Boltzmann constant and \( k = \epsilon_r \epsilon_0 \) is the electrical permittivity of the material \[33\]. Dielectric constants for disordered metals have not generally been reliably determined, only estimated \[31\]: independent of such estimates \( \epsilon_r \xi \) can be calculated from \( T_0 \). Taking \( \beta = 2.8 \) \[35\], we obtain \( \epsilon_r \xi = 1240 \) nm for the 0.37 mass-ratio film and \( \epsilon_r \xi = 880 \) nm for the 0.41 mass-ratio film. This is consistent with previous work \[31\] where \( \xi \) was found to be in the range of tens to hundreds of angstroms when \( \epsilon_r \) was estimated as \( 10^4 \). The high value of \( T_0 \) for the 0.34 mass-ratio film may indicate that this film is at the border of applicability of this model. Poor fits for the lower oxygen-content films indicate that conduction in those films is too metallic to be accurately predicted by the VRH model.
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was investigated. A transmission-line model test pat-
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be methods to use. Direct connection of the components
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was used as the strip material and chromium oxide was
area of each niobium-silicon-to-chromium-oxide contact
fabrication steps necessary. An alternative is to use
may be used by overlapping the components during depo-
In order to determine whether QPS nanowires could be
When connecting chromium oxide resistors to niobium-
sputter time of five minutes, leading to a film with a
composition of Nb
sputter deposition were used to produce a chromium
area of each niobium-silicon-to-chromium-oxide inter-
problem; we therefore investigated the contact resistance
Utilising a gold interlayer is a potential solution to this
by overlapping the components during deposition; this has the advantage of minimising the number of
An alternative is to use an inert non-oxidising interlayer, such as gold, to connect the two. This might be appropriate if direct contact
would result in too high a contact resistance.
In order to determine whether QPS nanowires could be
connected in series to chromium oxide resistors without
a large contact resistance, the contact resistance of the
interface between chromium oxide and niobium-silicon
was investigated. A transmission-line model test pat-
ttern was used to determine the contact resistance.
The model pattern consists of a series of pads of one
material spaced apart by varying distances, overlaid by a
strip of another material. The resistance between any two of these pads is
where
is the contact resistance between the pad and the strip,
is the resistance per unit length of the strip material and
is the length of strip between the two pads. Two-point measurements are performed for each pad combination and the known resistance of the pads is subtracted from this value in order to determine
On a plot of
against
, the
intercept conveniently gives the contact resistance.
The transmission-line model test patterns were fabri-
cated using photolithography. Initially, niobium-silicon
was used as the pad material and chromium oxide was
used as the strip material. First, a pattern of niobium-
silicon pads was created by lithography. Niobium-silicon
pads were co-deposited by sputtering using a 2" Nb tar-
gold to chromium oxide was 48 Ω, implying a specific
contact resistivity of 0.15 mΩcm² (15 kΩµm²). This is
several orders of magnitude less than the contact resist-
ance between niobium-silicon and chromium oxide. By
using gold as an intermediate layer, the contact resistance
was simultaneously deposited at 75 W, with a sputter time of five minutes, leading to a film with a composition of Nb
and a thickness of 70 nm.
After lift-off, a second lift-off mask and chromium ox-
ide sputter deposition were used to produce a chromium
oxide strip with a mass ratio of around 0.37 O/Cr. The
area of each niobium-silicon-to-chromium-oxide contact
was 5 × 30 µm². Aluminium bond wires were connected from the sample pads to copper pads that led to the
measurement equipment. Two-terminal resistance mea-
surements were made in the range ±10 µA between ev-
every pad combination at 4.2 K. The measured resistance
is dominated by the contact resistance and resistance of
the strip.
Fig. 5(a) shows the variation of the two-terminal re-
sistance as a function of the distance between the pads for the niobium-silicon-to-chromium-oxide interfaces.
 is 22 kΩ, implying a large specific contact resistivity of 65 mΩcm² (6.5 MΩµm²). For use in a circuit
for QPS current-standard experiments a contact area of a
few square microns is generally required. The contact
resistance for this interface would exceed the chromium
oxide resistance, and so is undesirably high.
Utilising a gold interlayer is a potential solution to this
problem; we therefore investigated the contact resistance
between chromium oxide and gold. To produce gold con-
tact pads, a 10 nm chromium adhesion layer, and after-
wards a 40 nm gold layer, were thermally evaporated and
then patterned using a positive photolithography resist
to define the pad shape. A wet-etch method was then
used to remove the unwanted metal and a solvent used to
remove any remaining resist. The chromium oxide strip
was then added, as before, using sputtering and a lift-
off process. Fig. 5(b) shows that the contact resistance
of gold to chromium oxide was 48 Ω, implying a specific
contact resistivity of 0.15 mΩcm² (15 kΩµm²). This is
several orders of magnitude less than the contact resis-
tance between niobium-silicon and chromium oxide. By
using gold as an intermediate layer, the contact resistance

| Mass Ratio O/Cr | $R_{(4.2\, K)}^{(\Omega/\square)}$ | $n$ | $T_0$ (K) | Fit $R^2$ |
|----------------|------------------|-----|---------|-----------|
| 0.18           | 65               | -   | -       | -         |
| 0.22           | 317              | -   | -       | -         |
| 0.34           | $1.1 \times 10^4$| 0.185 (± 0.006) | 41490 | 0.9996 |
| 0.37           | $9.5 \times 10^4$| 0.351 (± 0.004) | 474  | 0.9998 |
| 0.41           | $>2.0 \times 10^{10}$ | 0.534 (± 0.014) | 818  | 0.9988 |

TABLE I: Variation of the measured four-point resistance at 4.2 K for chromium oxide films of varying oxygen concentra-
tions. $R_{(4.2\, K)}$ is the measured sheet resistance at 4.2 K. Co-
cefficients of a fit to the equation $\ln R = \ln R_0 + (T_0/T)^n$ are
also shown. $R^2$ is the coefficient of determination and indi-
cates the goodness of fit. Fits for the 0.18 and 0.22 mass-ratio
films to this model were poor, associated with little change in
resistance across the temperature range.

IV. RESISTANCE OF CHROMIUM OXIDE INTERFACES FOR THE DEVELOPMENT OF A QPS CIRCUIT

FIG. 4: Optical image of a contact-resistance test pattern fab-
ricated with photolithography. Niobium-silicon pads of width
5 µm (± 1 µm) are in contact with a chromium oxide strip of
width 30 µm.
FIG. 5: (a). Variation of two-terminal contact resistance at 4.2 K with distance between contacts for a contact test pattern of NbSi (pads) and chromium oxide (strip). (b). Variation of two-terminal contact resistance with distance between contacts for a contact test pattern of gold (pads) and chromium oxide (strip). (Inset): Experimental set-up for the two-terminal measurements of each pair of pads. The resistance of the pads has been subtracted from the data before plotting.

at interfaces between different materials can therefore be minimised.

V. CONCLUSION

We have demonstrated that it is possible to reliably control the resistance of chromium oxide films at cryogenic temperatures by controlling the oxygen pressure at the time of deposition. Films can be sputtered with low-temperature sheet resistances in the range of MΩ–GΩ, far higher than currently obtained with standard thin-film resistor materials. For example two resistors with an O/Cr mass ratio of 0.34, thickness 100 nm, width of 65 nm and length of 2.1 µm will give a combined series resistance of above 60 kΩ at 50 mK. The films we deposited were found to be amorphous, with no magnetic phases present, which means they are suitable for use in superconducting circuits.

For fabrication of an on-chip circuit, gold or a similarly low-resistivity intermediate layer should be used to ensure a low contact resistance. Rapid oxidation of the surface of the films means careful consideration of the method of device manufacture and order of the layers is also needed.

For minimising temperature rises in a circuit at mK temperatures, strongly oxidised chromium-oxide resistors can be favourable compared with weakly oxidised resistors with the same value of resistance [11]. We also should verify that the parasitic capacitance does not result in a cut-off frequency too low for QPS applications: Using a value of capacitance per unit area for the resistors determined by Zorin et al. [15], we find a cut-off frequency of 5 GHz. This may be sufficiently high that the circuit dynamics are not affected.

We conclude that chromium oxide films are suitable for use for thin-film resistors with values in the range of hundreds of ohms to mega-ohms, and in particular are suited to use in applications such as QPS circuits.

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It is worth noting that some conduction through the semiconducting substrate is likely in such measurements.

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