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Intrinsic magnetic refrigeration of a single electron transistor

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In this work, we show that aluminium doped with low concentrations of magnetic impurities can be used to fabricate quantum devices with intrinsic cooling capabilities. We fabricate single electron transistors made of aluminium doped with 2% Mn by using a standard multi angle evaporation technique and show that the quantity of metal used to fabricate the devices generates enough cooling power to achieve a drop of 160 mK in the electron temperature at the base temperature of our cryostat (300 mK). The cooling mechanism is based on the magneto-caloric effect from the diluted Mn moments. © 2016 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4941289>]

Magnetic refrigeration is a cooling mechanism based on the magneto-caloric effect (MCE), in which a decrease in temperature is achieved by performing an adiabatic demagnetisation of a paramagnetic system. Magnetic refrigeration has stimulated much research after its first observation in 1881 by Warburg¹ for its potential to become a cleaner alternative to standard gas compression refrigeration. Gd-based ferromagnets, in which the MCE is observed up to room temperatures,² have been thoroughly investigated in the past years. More recently, the discovery of the enhancement of the MCE in correspondence of a first order magnetic transition³ has stimulated interest in new classes of materials, such as transition-metal-based and lanthanide-based compounds,⁴ manganites,⁵ Heusler compounds,⁶ and strained epilayers.^{7,8}

Although room temperature refrigeration remains a major focus of research, the MCE has been widely used for cryogenic applications. For this purpose, a few grams of paramagnetic salts allowed reaching sub-Kelvin temperatures.⁹ In this work, we show that aluminium doped with low concentrations of magnetic impurities can be used to achieve magnetic refrigeration. The ease with which these metal alloys can be patterned and integrated with micro-circuitry can be exploited to make quantum devices with intrinsic cooling capabilities. We demonstrate that the small quantity of metal used to form a single electron transistor (SET) is sufficient to decrease the electron temperature by 160 mK at the base temperature of our He³ insert cryostat (300 mK).

Since the first demonstration by Fulton and Dolan,¹⁰ aluminium SETs have found widespread use for sensitive and high bandwidth charge sensing,¹¹ and recent applications include phonon sensing.¹² In these applications, the signal to noise ratio and thus the detection performance of the device is significantly improved at low temperature.¹³ At the cryogenic temperatures where the aluminium SETs are usually operated, these devices become superconducting, causing a gap to open in the lead and island density-of-states. In case that superconductivity is not desirable, perhaps due to the need for magnetic field independent electrical transport, it is possible to dope the aluminium. A diluted concentration of magnetic impurities is known to suppress the superconductivity of the aluminium even at very low temperatures.¹⁴ Here we show that manganese doped aluminium not only suppresses the

superconductivity of aluminium, but exhibits the MCE, acting as an intrinsic refrigerator for the single electron device.

Mn-doped Al has been used in the past to fabricate ultra-low temperature bolometers based on superconducting-insulating-normal metal tunnel junctions.¹⁵ In these devices, it was possible to reduce the electronic temperature from 260 to 130 mK by removing hot electrons via tunneling from the normal metal to the superconductor;¹⁶ our devices, on the other hand, are entirely made of AlMn and the cooling mechanism is based on the MCE in this material and is thus less subject to the device specifics, such as quality and dimensions of the junctions and thickness of the leads.

Al₉₈Mn₂ SETs were fabricated by standard double angle evaporation technique using a controlled oxygen atmosphere at a pressure of 2.5×10^{-2} mbar to create the tunneling junctions between the source (S) and drain (D) leads and the central island. This procedure resulted in a source to drain resistance of ~ 200 k Ω at 300 mK. Fig. 1(a) shows a scanning electron micrograph of the SET. The overlapping area between the island and each lead is 50×50 nm² while the thickness of the metal in correspondence of the device is 20 nm (the thickness in correspondence of the bond-pads is doubled due to the nature of the double angle evaporation technique). The SET was fabricated on top of a conducting layer, which acted as back-gate, and was electrically insulated from it by an 80 nm thick alumina layer, grown by atomic layer deposition. Although the analysis has been partly performed on SETs with a (Ga,Mn)As magnetic back-gate, we will show that the nature of the back gate is not important for the effect that we discuss in this work. Two side gates were also present and could be used equivalently to the back gate to modulate the device conductance.

Fig. 1(b) shows the differential conductance of the Al₉₈Mn₂ SET as a function of the source-drain and back-gate voltages and in zero magnetic field. This measurement was performed at the cryostat temperature $T = 300$ mK. To avoid confusion, in what follows we will refer to the cryostat temperature as the temperature measured by the thermometer near the He³ pot of our cryostat and we will simply label it as T , while the electron temperature of the device will be labeled as T_e . The diamonds are characteristic of the Coulomb-blockade (CB) transport regime; from them we calculate the single-

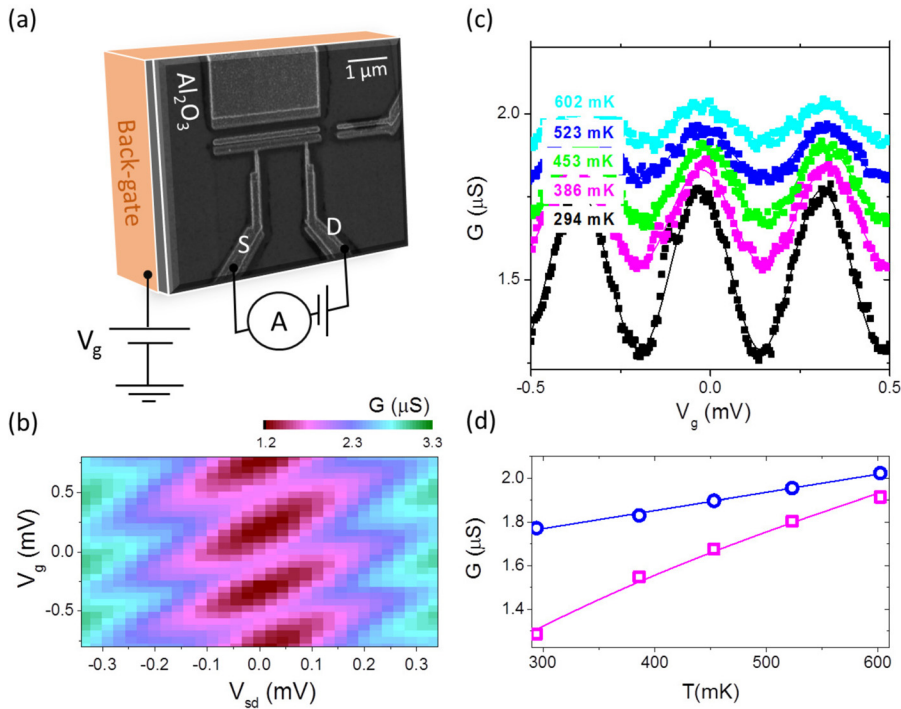


FIG. 1. (a) Device layout showing a micrograph of the $\text{Al}_{98}\text{Mn}_2$ -SET and the back gate. The source and drain leads are labelled as S and D, respectively. (b) Differential conductance of the SET measured at $T = 300$ mK as a function of the source-drain voltage and back-gate voltage. (c) CB oscillations measured at different cryostat temperatures. The continuous line represents a fitting to the orthodox theory in classical transport regime. (d) Maximum (blue circles) and minimum (pink squares) values of the SET conductance oscillations extrapolated from (c) as a function of the cryostat temperature T and fixed $V_{\text{sd}} = 20 \mu\text{V}$. The continuous lines represent a fitting to the orthodox theory of the SET in classical regime (continuous density of states).

electron charging energy $E_c = 150 \mu\text{eV}$. In Fig. 1(c) we report single traces at fixed source-drain voltage $V_{\text{sd}} = 20 \mu\text{V}$ and different cryostat temperatures. For this measurement no magnetic field was applied and the device was in thermal equilibrium with the cold finger. As the back-gate voltage is swept, the device alternates between blockade and transport regimes, which results in oscillating conductance. From the period of the oscillations we determine the coupling capacitance to the back gate $C_{\text{BG}} \sim 0.5$ fF. As thermal energy increases Coulomb blockade becomes less effective, resulting in a decreased visibility in the conductance oscillations. Fig. 1(d) shows the conductance maximum and minimum with respect to temperature extracted from Fig. 1(c). The continuous lines represent a fitting to the orthodox theory of the SET in the classical transport regime.¹⁷ From the fitting we have extrapolated a value of $E_c = 130 \mu\text{eV}$, in good agreement with the value found from the conductance diamonds in Fig. 1(b). This fitting constitutes the calibration curve that will allow us to estimate the electron temperature from the maximum and minimum values of the SET conductance.

Fig. 2(a) constitutes the main observation of this work, showing the SET conductance oscillations at different values

of the magnetic field, from -1.3 T to 1.3 T. When the magnetic field approaches zero, the oscillations become narrower and deeper, whereas they appear broader and shallower when the magnetic field is increased from zero. The measurements presented in this work were all carried in a high magnetic field cryostat that allowed the application of fields up to 12 T in the direction perpendicular to the plane of the device. The effect is, however, independent on the direction of sweep, as we have established by repeating the measurement in a lower-field cryostat that allowed in-plane sweeps. We extract the electron temperature from the amplitude of the conductance oscillations according to the calibration in Fig. 1(d). Fig. 2(b) shows the electron temperature T_e as a function of magnetic field for two directions of sweep. Regardless of the direction of sweep, as zero magnetic field is crossed, T_e decreases and then increases again by approximately 80 mK. It is important to emphasize that this is a local effect as no temperature change is registered on the thermometer near the He^3 pot of our cryostat.

This behaviour is understood in terms of the magneto-caloric effect, which describes the adiabatic change in temperature of a paramagnetic system near the ordering temperature

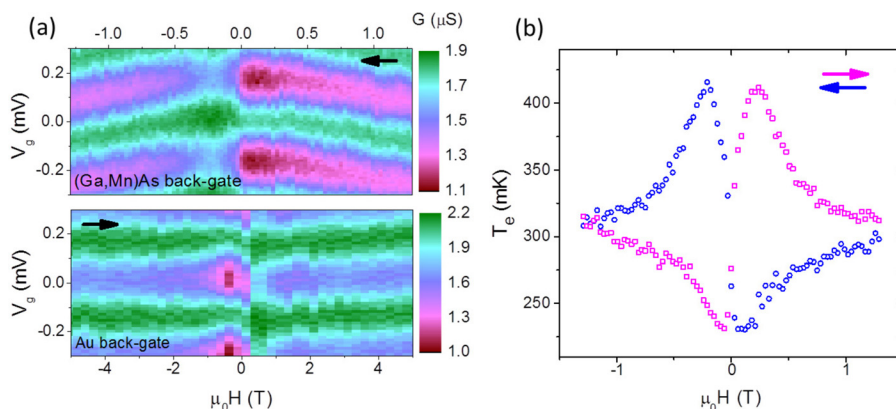


FIG. 2. (a) CB oscillations measured at different values of the out-of-plane magnetic field for an $\text{Al}_{98}\text{Mn}_2$ -SET with a (Ga,Mn)As back gate (top) or a Au back gate (bottom). The field is swept in the direction of the black arrow at the rate of 0.3 T/min. (b) Electron temperature of the SET as a function of magnetic field, deduced by CB thermometry (Fig. 1(c)).

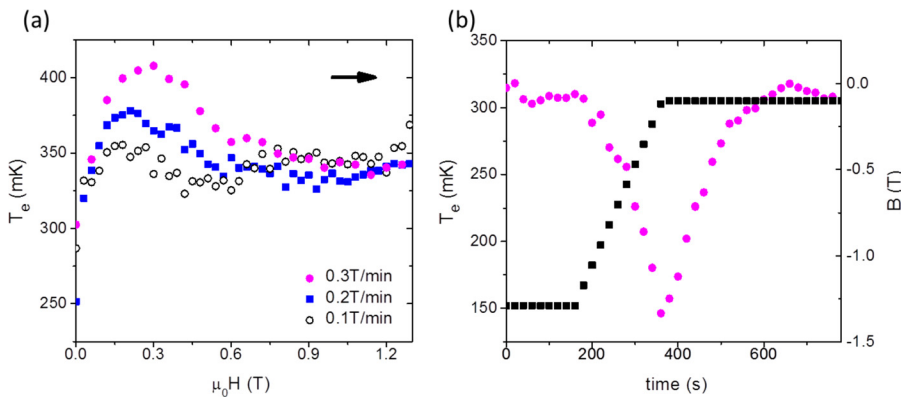


FIG. 3. (a) Electron temperature of the SET as a function of out-of-plane magnetic field, swept from 0 T to 1.4 T at different rates. (b) Variation in the electron temperature of the SET as a function of time when an out-of-plane magnetic field is swept from -1.3 T to -0.1 T in 200 seconds. The electron temperature decreases by 160 mK during the ramping and equilibrates again to the original value when the ramping is interrupted, with a time constant of about 200 seconds.

when a magnetic field is applied. The total entropy of such system is the sum of two contributions: a magnetic contribution depending on the magnetic ordering of the spins and a thermal contribution depending on temperature. When the system is adiabatically magnetised the magnetic disorder is reduced, leading to a decrease of the magnetic component. Because the process is adiabatic the total entropy must remain constant, which leads to an increase in the thermal component, and thus heating. On the other hand, when the system is adiabatically demagnetised, the magnetic component of the entropy increases and the system undergoes refrigeration.

In this case, the system of spins that induces the MC effect is represented by the magnetic moments of the diluted Mn atoms, while the particularly weak electron-phonon coupling¹⁸ guarantees good thermal isolation from the 300 mK He³ pot.

Although we observe the MCE far from the Curie temperature of the (Ga,Mn)As substrate ($T_c \sim 80$ K), it was observed that at sub-Kelvin temperature a super-paramagnetic phase might coexist with the ferromagnetic phase in this material.^{25,26} To confirm that the MCE originates in the AIMn rather than in the super-paramagnetic phase of the substrate, we have repeated the magnetic field sweeps measurements for identical Al₉₈Mn₂-SETs with a gold back-gate. As shown in Fig. 2(a) (bottom) a similar change in T_e is measured as the magnetic field is swept through zero, indicating that the magneto-caloric effect does not originate in the gate.

The moment of an isolated Mn atom in bulk aluminium was calculated in Ref. 19 to be $1 \mu_B$, corresponding to a saturation magnetisation of 17 kA/m for 2% doping concentration. The Mn magnetic moments that give rise to the MC effect are sufficiently diluted to neglect dipolar interactions and are modelled as an ensemble of non-interacting magnetic moments.

Although a rigorous treatment would involve calculating the entropy change from its quantum expression,²⁰ we can estimate its value from the Clausius–Clapeyron equation

$$\left| \frac{\Delta H}{\Delta T} \right| = \left| \frac{\Delta S}{\Delta M} \right|, \quad (1)$$

where $\Delta S = S_1 - S_2$ and $\Delta M = M_1 - M_2$ represent the difference in magnetic entropy and magnetisation of the two phases when the magnetic field is swept from H_1 to H_2 , with $\Delta H = H_1 - H_2$.²¹

Because of the non-perfect thermal isolation, the change in the electron temperature induced by a change in magnetic field depends on the rate at which the magnetic field is swept.

If this rate is too low compared with the rate with which the device exchanges heat with the surrounding, thermal equilibrium with the cold finger is maintained and no temperature variation is measured, as shown in Fig. 3(a). Fig. 3(b) shows that when the magnetic field is swept from -1.3 T to -0.1 T at a rate of 0.36 T/min, T_e decreases by 160 mK and re-equilibrates 200 s after the end of the sweep. From this measurement, we estimate that $\left| \frac{\Delta H}{\Delta T} \right| \sim 7.4$ T/K and calculate that $\Delta S \sim 130$ mJ/K cm³, a value comparable with the value reported for other amorphous systems, such as diluted magnetic nano-particles²² and amorphous alloys.^{23,24} In order to compare the cooling performance of Mn-doped Al with that of other alloys, a useful figure of merit is the *Coefficient of Refrigerant Performance* (CRP), defined as the ratio between refrigerant capacity and positive work on the refrigerant.²⁷ The refrigerant capacity is defined as $|\Delta S_M \Delta T|$, where $\Delta S_M = \int_{H_1}^{H_2} \left(\frac{\partial M(H,T)}{\partial T} \right)_H dH$ is the magnetic entropy change, while the work done by the magnetic field on the magnetic moments of the Mn atoms is $\int_{H_1}^{H_2} M(H,T) dH$. By considering the Mn moments as isolated, we define the magnetization per spin as a function of temperature and field as $M(H,T) = \mu_B \left(\frac{1 - e^{-\mu_B H/k_B T}}{1 + e^{-\mu_B H/k_B T}} \right)$.²⁸ For our system, we obtain $\text{CRP} = 0.7$, which is a value comparable with that of top class magnetocaloric alloys.²⁹

In conclusion, we have demonstrated magnetic cooling for a single electron device via the magneto-caloric effect in aluminium-manganese. Regardless of the small quantity of metal used and the dilute concentrations of magnetic impurities (2%), temperature variations of up to 160 mK were recorded in the electron temperature from 300 mK. The easiness with which the aluminium-based alloys are patterned makes the designing of “on-chip” refrigerators and the integration with microwave circuitry straightforward to achieve.

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