A thin-film cryotron suitable for use as an ultra-low-temperature switch

Peter J. Lowell, John A. B. Mates, W. Bertrand Doriese, Gene C. Hilton, Kelsey M. Morgan, Daniel S. Swetz, Joel N. Ullom, and Daniel R. Schmidt

Citation: Appl. Phys. Lett. **109**, 142601 (2016); doi: 10.1063/1.4964345
View online: http://dx.doi.org/10.1063/1.4964345
View Table of Contents: http://aip.scitation.org/toc/apl/109/14
Published by the American Institute of Physics

APPLIED PHYSICS LETTERS **109**, 142601 (2016)

A thin-film cryotron suitable for use as an ultra-low-temperature switch

Peter J. Lowell,[1,a)] John A. B. Mates,[2] W. Bertrand Doriese,[1] Gene C. Hilton,[1] Kelsey M. Morgan,[1] Daniel S. Swetz,[1] Joel N. Ullom,[1,2] and Daniel R. Schmidt[1,b)]
[1]*National Institute of Standards and Technology, Boulder, Colorado 80305, USA*
[2]*University of Colorado, Boulder, Colorado 80309, USA*

(Received 18 August 2016; accepted 22 September 2016; published online 6 October 2016)

Low-temperature superconducting circuits have become important for many scientific applications. However, there are presently no high current-capacity switches ($\sim$1 mA) with low power dissipation for sub-Kelvin operation. One candidate for a sub-Kelvin switch is the cryotron, a device in which the superconductivity of a wire is suppressed with a magnetic field. Here, we demonstrate a cryotron switch suitable for sub-Kelvin temperatures. In the closed state, the maximum device current is about 900 μA. The device is switched to its open state with 2 mA of control current and has a leakage of approximately 500 nA. The transition between the closed and open states of the device is faster than 200 ns, where the measurement is limited by the speed of our measurement apparatus. We also discuss low-temperature applications for our cryotron such as a single-pole, double-throw switch. [http://dx.doi.org/10.1063/1.4964345]

Superconducting circuitry for applications such as quantum[1] and low-power classical[2] computing, quantum optics,[3] and low-temperature detectors,[4,5] has become increasingly mature and complex. In these circuits, there is a demand for switching technologies that can be used to reduce the total wire count and increase circuit programmability. Present superconducting switches include thin-film electrothermal devices[6] and tunnel-junction-based switches. In electrothermal switches, actuation current creates a hot spot that suppresses the superconductivity of a wire. The associated power dissipation may prohibit some large scale implementations. Tunnel-junction-based switches[7–9] can operate at sub-Kelvin temperatures, but either have high current-capacity with high leakage current or low current-capacity with low leakage current. In this letter, we demonstrate a high current-capacity ($\sim$1 mA) cryotron switch that requires a low actuation current and is suitable for use at sub-Kelvin temperatures.

First demonstrated by Buck in 1956,[10] a cryotron consists of a superconducting switching element, called the *signal*[11] line, and a magnetic coil, called the *control* line, as shown in Figure 1(a). To switch the device, current is driven through the control line until it applies a field greater than the critical field of the signal line and thus drives the signal line normal. As a simple superconducting wire, the cryotron has a high supercurrent capacity in its closed state and a low supercurrent leakage in its open or resistive state. These properties make it an ideal building block for a switch.

Since the first demonstration, many improvements were made to cryotron devices.[12–15] Much of this work was devoted to creating switches suitable for use in logic gates, which led to the optimization of switches to produce gain instead of a device that operated at low temperatures. For example, these early devices were operated at 90% of their critical temperature, T_c, to decrease the signal line critical field, H_c, and thus decrease the necessary control current. While this reduced the required control current to tens or hundreds of milliamps, a requirement to operate near its T_c is not desirable for a general-purpose, sub-Kelvin switch. Additionally, these early devices operated at 4 K where the cooling power of refrigerators was large enough that the Joule heating due to small parasitic resistances in the control line was of no concern. At sub-Kelvin temperatures, refrigerators have cooling powers on order of 1–100 μW, so the parasitic power load (10 nW–1 μW per device) caused by 10–100 mA passing through a typical contact resistance of a connector (100 $\mu\Omega$) will substantially heat the sample box if multiple devices are used. Therefore, devices with lower actuation currents are required for sub-Kelvin operation.

For use as a low temperature switch, an ideal cryotron needs to operate at temperatures well below the signal-line T_c and have smaller actuation current than demonstrated in the previous devices. We selected materials suited for low temperatures and increased the magnetic field applied to the signal line for a given control current via a superconducting transformer. A suitable signal-line material is Al doped with Mn (AlMn) because of its large normal-state resistance and tunable T_c.[16] As a thin film, we assume AlMn behaves as a type-II superconductor. We targeted a critical temperature of 250 mK and a normal-state resistivity of 3×10^{-8} Ω m. To estimate H_c of bulk AlMn, we scale the measured value for Al, $H_c = 10.5$ mT,[17] by the ratio of the Al and AlMn critical

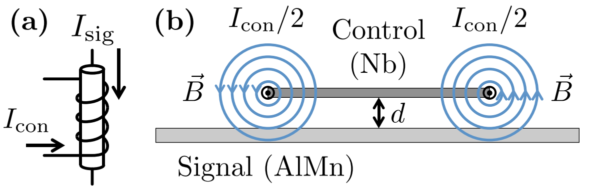

FIG. 1. (a) Diagram of a cryotron device. The signal line is a superconducting wire that can be driven normal by a magnetic field created by current in the control line. (b) Schematic of our cryotron model. Since the device is operated far below the T_c of Nb, the current in the Nb travels at the edge of the wire. This current creates a magnetic field that can drive the signal line, located a distance d away, normal.

[a)]Electronic mail: peter.lowell@nist.gov
[b)]Electronic mail: dan.schmidt@nist.gov

temperatures according to BCS theory. Using this method, we estimate that H_c for our AlMn is 2 mT. The H_{c1} of the AlMn thin film should not exceed this value.

To estimate the control current required to produce this magnetic field, we used the toy model shown in Figure 1(b). We chose Nb for the control line material because of its high critical temperature and high critical-current density. The control line crosses over the AlMn signal line at a distance d. At currents much less than the critical current of the Nb control line, the control current preferentially concentrates at the edge of the wire,[18] which creates approximately the magnetic field shown in Figure 1(b).

According to the Ginzburg-Landau equations, a perpendicular magnetic field is much more effective at suppressing superconductivity than a parallel magnetic field of the same magnitude. Therefore, the control current that produces a perpendicular magnetic field component that exceeds H_c will actuate the switch. The magnetic field with the maximum perpendicular component occurs at a distance of $\sqrt{2}d$ from the edge of the wire, and its magnitude is $B_{\perp\max} = \mu_0 I_{con}/(8\pi d)$ where I_{con} is the full control current and d is the distance between the control line and signal line. Thus, 4 mA is required to generate 2 mT for $d = 100$ nm, at typical thickness of a fabricated insulator.

While $I_{con} = 4$ mA is smaller than in previous devices, even lower actuation currents can be achieved using a superconducting transformer. In our prototype device, the 10 μm wide AlMn signal line is insulated by a 100 nm thick layer of SiO_2, and crossed over by 3 μm wide Nb control-line traces which extend from a superconducting washer. The washer forms the secondary of a superconducting transformer with a 20-turn Nb primary coil. Through device modeling, we estimate that this transformer produces a current in the superconducting washer that is about 10 times larger than the control current, reducing the estimated actuation current that must be supplied to the control line to below 1 mA. A completed device is pictured in Figure 2. We also fabricated devices with a superconducting dipole-gradiometer washer to reduce measurement offsets caused by stray magnetic fields; a micrograph of this device is shown in the supplementary material. For more information on device fabrication, see supplementary material.

The following measurements were performed on a dipole-gradiometer cyotron. Devices were measured in a magnetically shielded adiabatic demagnetization refrigerator (ADR) thermally regulated at 70 mK.[19] Current bias was achieved with a low-noise voltage source in series with a large bias resistor, and the voltage across the signal line was measured with a volt meter. We measured the signal line to have $T_c = 245$ mK and the critical current of the control line to be greater than 5 mA. We then performed the current-voltage (IV) measurements of the signal line to determine the signal current at which R_{signal} exceeded 50 mΩ, our operational definition of the open state. Measurements were performed for both positive and negative signal and control currents to determine any offsets. The results of these measurements are shown on a log scale in Figure 3 and on a linear scale in the supplementary material. As the data show, when no current is applied to the control line, the maximum signal-line supercurrent is $I_{sig} = 900$ μA. For applied fields

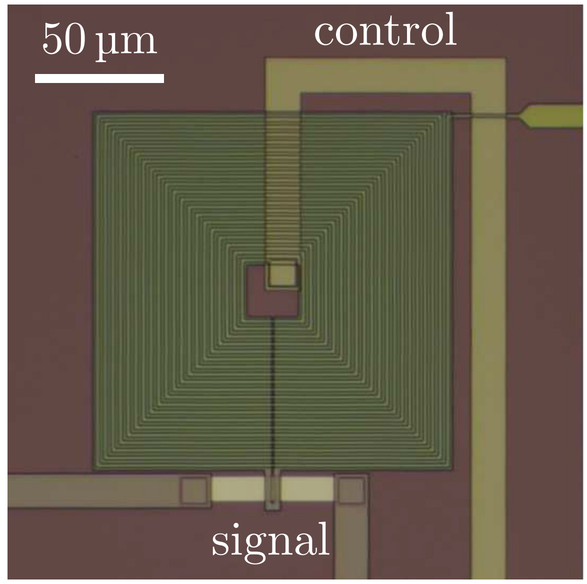

FIG. 2. Micrograph of our cryotron switch. The signal line is a 10 μm-wide strip of AlMn. Current in the Nb control line applies a magnetic field to the signal line. Current is applied to a 20-turn primary coil of a transformer whose secondary coil is in close proximity to the AlMn signal line.

below H_{c2}, the device will always allow a small supercurrent to flow. As the control current is increased, this supercurrent is reduced. At $I_{con} = 2$ mA, the critical current of the signal line is reduced to the detectable limit of our measurement apparatus, approximately 500 nA. Previous cryotron devices had an actuation current in the tens of milliamps when operated within 90% of the T_c of the signal line,[14] so this result is a factor of 10 times less actuation current than in previous devices at a temperature less than 30% of the T_c of the signal line.

The data trend agrees with previous results, in that our device exhibits a low-field regime with a steep linear slope, which represents the squeezing of the current in the Meissner state, and a high-field regime with a long decaying tail, which represents the current in the presence of vortices.[18,20,21] However, the theories predict the transition between the two regimes at a magnetic field an order of magnitude smaller than we observe. We hypothesize that this discrepancy is because we do not apply the uniform, perpendicular, magnetic field to the device that the theory

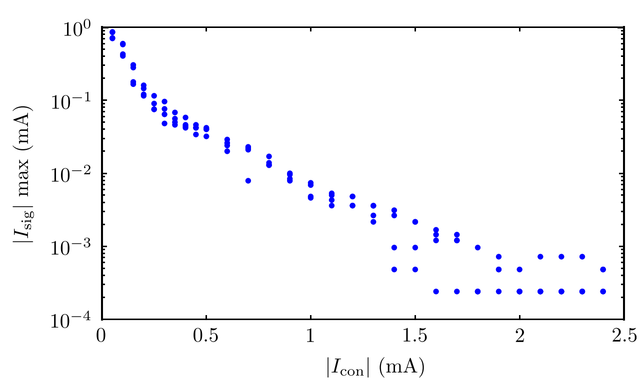

FIG. 3. Multiple measurements of the magnitude of the maximum supercurrent, I_{sig} max, that can flow through the signal line before at least 50 mΩ is measured across the signal line versus the magnitude of the control line current at 70 mK.

expects. In future work, we will measure I_c suppression in new devices in a more uniform perpendicular magnetic field to better understand and resolve the discrepancy.

At $I_{con} = 2$ mA, the signal line has a resistance of about 150 mΩ for signal current lower than 6 μA. We hypothesize that the control current is only driving a small region of the signal line normal. Higher signal currents with $I_{con} = 2$ mA drive the entire length of the signal line normal, and we observe a signal-line resistance of about 3.4 Ω. While 150 mΩ is a useful switching resistance for completely superconducting circuits, other applications may require a larger normal-state resistance. This could be accomplished by meandering the control wire over the signal wire to create more crossings of the signal and control lines which would drive more regions in the signal line normal.

The theoretical description of cryotron switching dynamics uses the time-dependent Ginzburg-Landau equations, which describe the pinching of the superconducting state into the center of a wire as magnetic field gradually penetrates from the edges as well as other phenomena, such as the electron-phonon coupling which removes the latent heat of superconductivity as the signal line returns to its closed state. These equations predict switching speeds on the order of nanoseconds, and cryotrons in the literature have demonstrated speeds as fast as 40 ns.[22]

While we believe there may be a large number of applications for such a device, we were particularly interested in its compatibility with our multiplexed SQUID readout, which we operate at switching times as low as ~200 ns.[23] We therefore integrated a cryotron into a parallel circuit where the current is shunted from the signal line to the input coil of a SQUID to verify that the cryotron does not limit the switching speed of our SQUID electronics. Measurements (shown in the supplementary material) demonstrate that the cryotron does not limit the switching speed of our multiplexed SQUID readout electronics and place an upper limit of 200 ns on the switching time of the cryotron.

Using our measured values of the device resistance and switching speed, we can estimate the switching energy. Because the transition between the normal and superconducting states is a reversible process, no energy is deposited into the closed system by this phase transition. Instead, energy is deposited into the system from Joule heating of the signal line integrated over the switching time. Assuming a switching time of 200 ns, a signal-line resistance of 150 mΩ, and a maximum signal-line current of 900 μA, 12 fJ is deposited per switching event. In addition to the energy deposited per switching event, if the entire 500 nA leakage current passes through 150 mΩ signal line, we estimate an additional power load of only 40 fW in the open state.

The cryotron already shown can be used as a single-pole, single-throw switch. However, many applications require the ability to *steer* supercurrent. To this end, we also designed and fabricated a single-pole, double-throw (SPDT) switch that allows the current to follow a superconducting path by connecting the signal lines of two cryotron devices together. A diagram of this circuit is shown in Figure 4 and a micrograph of the device is shown in the supplementary material. In normal operation, current enters the switch through the center signal line lead (terminal 2) and exits the

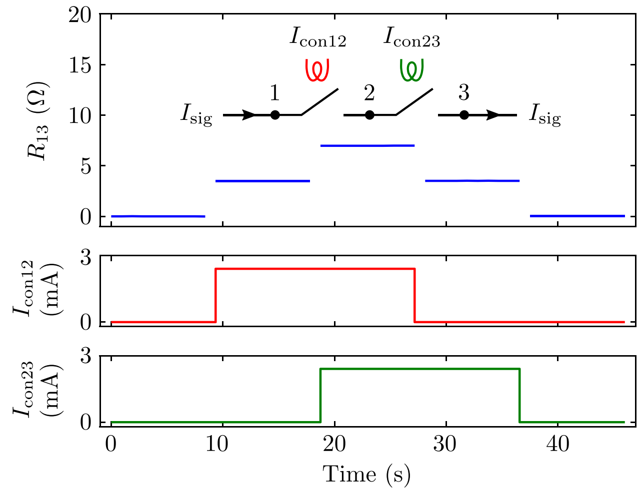

FIG. 4. (upper figure) R_{sig} versus time of the SPDT device (schematic shown in inset). The blue lines are the measured values of both signal lines, the red line (middle figure) is the current applied to control 1, and the green line (bottom figure) is the current applied to control 2.

switch through the signal line branch that is superconducting. The current can be steered to the right or to the left by driving the appropriate signal line normal. Unfortunately, we were not able to test our device in this fashion because the change in the signal line resistance (from 0 to 3.5 Ω) is significantly smaller than the line resistance from the cryotron to the outside world. Therefore, to test the device, we measured the resistance of both signal lines by running 5 μA from signal line terminal 1 to signal line terminal 3 and measured the voltage across these two nodes. We then varied the control line current of the two cryotrons as shown in Figure 4.

When both switches are closed, $R_{sig} = 0$ Ω. When just one switch is actuated to the open state, $R_{sig} = 3.5$ Ω and when both switches are open, $R_{sig} = 7$ Ω. This measurement demonstrates functionality in both switches, and we expect to demonstrate integration with other superconducting circuitry soon.

The switches that we have demonstrated will have an immediate impact. For example, the dominant source of crosstalk in time division SQUID multiplexing[24] is parasitic coupling of feedback current to the inputs of all SQUIDS in a readout column. Our switch could shunt this feedback current so that it couples only to the active SQUID, thus eliminating this form of crosstalk. Other applications include: code-division SQUID multiplexing,[9,25] a binary-switching network that routes one input to 2^N outputs, and tunable coupling strength in circuits for quantum computing to resolve tension between communication and coherence.

While we were able to reduce the actuation current from that of the previous cryotron devices, some applications may require even lower actuation current. This could be accomplished with more turns in the primary coil of the transformer. In space-limited applications, cell size could be reduced by creating the primary coil using e-beam lithography.

In conclusion, we have demonstrated a cryotron switch with a maximum $I_{sig} = 900$ μA in its closed state ($I_{con} = 0$ A) and a leakage current $I_{sig} \sim 500$ nA in its open state ($I_{con} = 2$ mA) that can operate at temperatures far below the signal line T_c. The cryotron switches faster than 200 ns. We integrated two cryotron switches into a SPDT switch and demonstrated its operation. These properties make our cryotron a useful switching method for sub-Kelvin superconducting circuits.

See supplementary material for information on device fabrication, micrographs of the various cryotron designs, and more information on the dc and speed measurements.

We gratefully acknowledge the financial support from NIST Innovations in Measurement Science Program, and NASA through the grants "Providing, enabling, and enhancing technologies for a demonstration model of the Athena X-IFU," NASA NNG16PT18I, and "Demonstrating Enabling Technologies for the High-Resolution Imaging Spectrometer of the Next NASA X-ray Astronomy Mission," NASA NNH11ZDA001N-SAT. P. Lowell and K. Morgan are supported by the National Research Council Post-Doctoral Fellowships. Contribution of NIST is not subject to copyright in the United States.

[1]T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe, and J. L. O'Brien, "Quantum computers," Nature **464**, 45–53 (2010).
[2]D. S. Holmes, A. L. Ripple, and M. Manheimer, "Energy-efficient superconducting computing power budgets and requirements," IEEE Trans. Appl. Supercond. **23**, 1701610 (2013).
[3]J. You and F. Nori, "Atomic physics and quantum optics using superconducting circuits," Nature **474**, 589–597 (2011).
[4]C. Enss, *Cryogenic Particle Detection* (Springer Science & Business Media, 2005), Vol. 99.
[5]J. N. Ullom and D. A. Bennett, "Review of superconducting transition-edge sensors for x-ray and gamma-ray spectroscopy," Supercond. Sci. Technol. **28**, 084003 (2015).
[6]A. N. McCaughan and K. K. Berggren, "A superconducting-nanowire three-terminal electrothermal device," Nano Lett. **14**, 5748–5753 (2014).
[7]H. Zappe, "Josephson quantum interference computer devices," IEEE Trans. Magn. **13**, 41–47 (1977).
[8]J. Beyer and D. Drung, "A squid multiplexer with superconducting-to-normal conducting switches," Supercond. Sci. Technol. **21**, 105022 (2008).
[9]M. Niemack, J. Beyer, H. Cho, W. Doriese, G. Hilton, K. Irwin, C. Reintsema, D. Schmidt, J. Ullom, and L. Vale, "Code-division squid multiplexing," Appl. Phys. Lett. **96**, 163509 (2010).
[10]D. A. Buck, "The cryotron-a superconductive computer component," Proc. IRE **44**, 482–493 (1956).
[11]Historically, this line was called the gate but we use signal to avoid confusion due to the contrary usage in the field-effect transistor.
[12]V. Newhouse and J. Bremer, "High-speed superconductive switching element suitable for two-dimensional fabrication," J. Appl. Phys. **30**, 1458–1459 (1959).
[13]V. Newhouse, J. Bremer, and H. Edwards, "The crossed-film cryotron and its application to digital computer circuits," papers presented at the Eastern Joint IRE-AIEE-ACM Computer Conference, December 1–3, 1959 (ACM, 1959), pp. 255–260.
[14]V. Newhouse, J. Bremer, and H. Edwards, "An improved film cryotron and its application to digital computers," Proc. IRE **48**, 1395–1404 (1960).
[15]A. Brennemann, "The in-line cryotron," Proc. IEEE **51**, 442–451 (1963).
[16]D. Schmidt, H.-M. Cho, J. Hubmayr, P. Lowell, M. Niemack, G. Neil, J. Ullom, K. Yoon, K. Irwin, W. Holzapfel *et al.*, "Al-Mn transition edge sensors for cosmic microwave background polarimeters," IEEE Trans. Appl. Supercond. **21**, 196–198 (2011).
[17]E. P. Harris and D. Mapother, "Critical field of superconducting aluminum as a function of pressure and temperature above 0.3 K," Phys. Rev. **165**, 522 (1968).
[18]E. H. Brandt and M. Indenbom, "Type-II-superconductor strip with current in a perpendicular magnetic field," Phys. Rev. B **48**, 12893 (1993).
[19]D. Bennett, R. Horansky, D. Schmidt, A. Hoover, R. Winkler, B. Alpert, J. Beall, W. Doriese, J. Fowler, C. Fitzgerald *et al.*, "A high resolution gamma-ray spectrometer based on superconducting microcalorimeters," Rev. Sci. Instrum. **83**, 093113 (2012).
[20]M. Benkraouda and J. R. Clem, "Critical current from surface barriers in type-II superconducting strips," Phys. Rev. B **58**, 15103 (1998).
[21]K. Ilin, D. Henrich, Y. Luck, Y. Liang, M. Siegel, and D. Y. Vodolazov, "Critical current of Nb, NbN, and TaN thin-film bridges with and without geometrical nonuniformities in a magnetic field," Phys. Rev. B **89**, 184511 (2014).
[22]A. Brennemann, J. McNichol, and D. Seraphim, "Delay times for switching in-line cryotrons," Proc. IEEE **51**, 1009–1014 (1963).
[23]W. Doriese, K. Morgan, D. Bennett, E. Denison, C. Fitzgerald, J. Fowler, J. Gard, J. Hays-Wehle, G. Hilton, K. Irwin *et al.*, "Developments in time-division multiplexing of x-ray transition-edge sensors," J. Low Temp. Phys. **184**, 389–395 (2016).
[24]J. Chervenak, K. D. Irwin, E. N. Grossman, J. M. Martinis, C. D. Reintsema, and M. Huber, "Superconducting multiplexer for arrays of transition edge sensors," Appl. Phys. Lett. **74**, 4043–4045 (1999).
[25]K. Irwin, H. Cho, W. Doriese, J. Fowler, G. Hilton, M. Niemack, C. Reintsema, D. Schmidt, J. Ullom, and L. Vale, "Advanced code-division multiplexers for superconducting detector arrays," J. Low Temp. Phys. **167**, 588–594 (2012).