Radio Frequency Tunable Oscillator Device Based on a SmB$_6$ Microcrystal

Alex Stern, Dmitry K. Efimkin, Victor Galitski, Zachary Fisk, and Jing Xia

Department of Physics and Astronomy, University of California, Irvine, California 92697, USA
Joint Quantum Institute and Condensed Matter Theory Center, University of Maryland, College Park, Maryland 20742-4111, USA

(Received 12 January 2016; published 20 April 2016)

Radio frequency tunable oscillators are vital electronic components for signal generation, characterization, and processing. They are often constructed with a resonant circuit and a “negative” resistor, such as a Gunn diode, involving complex structure and large footprints. Here we report that a piece of SmB$_6$, 100 $\mu$m in size, works as a current-controlled oscillator in the 30 MHz frequency range. SmB$_6$ is a strongly correlated Kondo insulator that was recently found to have a robust surface state likely to be protected by the topology of its electronic structure. We exploit its nonlinear dynamics, and demonstrate large ac voltage outputs with frequencies from 20 Hz to 30 MHz by adjusting a small dc bias current. The behaviors of these oscillators agree well with a theoretical model describing the thermal and electronic dynamics of coupled surface and bulk states. With reduced crystal size we anticipate the device to work at higher frequencies, even in the THz regime. This type of oscillator might be realized in other materials with a metallic surface and a semiconducting bulk.

DOI: 10.1103/PhysRevLett.116.166603
scale with the surface area, suggesting its relevance to the
surface state. The oscillation behavior does not depend on
the exact geometry of the crystal: as shown in the inset of
Fig. 1 this oscillator is based on a rather irregularly shaped
SmB\textsubscript{6} sample. The output of this oscillator can be con-
tinuously tuned from 29 to 33 MHz by varying \( I_0 \) between
0 and 4 mA. Shown in Fig. 1(a) are outputs for three represen-
tative \( I_0 = 0.47, 1.56, \) and 2.42 mA. And the
Fourier transformations are shown in Fig. 1(b), showing
a typical full width at half maximum (FWHM) spectral
width \( \Delta f \) of only 0.05 MHz. We note that this is achieved
without a phase-locked loop circuit.

We find that the center frequency, which is the frequency
where maximum oscillation amplitude occurs, rises quickly
with smaller SmB\textsubscript{6} crystals. Plotted in Fig. 2(a) are the
center frequencies for a few representative oscillators of
various sizes and geometries, versus their surface areas,
which we found to show the highest correlation to center
frequency, compared to volume or any single dimension.
Projecting the frequency-surface area scaling further, we
speculate that THz oscillations might occur for
10-\( \mu \)m-sized crystals. Operation above 2 THz is unlikely due to the
3.5 meV bulk activation gap in SmB\textsubscript{6}. For each device,
a range of external capacitors can be used to generate
oscillations, as illustrated in Fig. 2(f) with no need for an
external capacitor for the two highest frequency devices
(29 and 31 MHz).

Both surface and bulk states are found to be essential for
oscillation to occur. The oscillation amplitude diminishes at
temperatures above 4 K, when bulk conduction dominates,
or below 1 K, when surface conduction prevails. Optimal
operation occurs at around 2 K when both the bulk and
surface contribute to the electric conduction. This trend
can be seen in the Supplemental Material [20], Fig. S2(c).
It is known that in SmB\textsubscript{6}, magnetic dopants such as Gd
destroy the conductive surface state [12], while inducing
little change to the bulk insulating gap. We fabricated
several devices using crystals from the same 3\% Gd
doped SmB\textsubscript{6} growth batch as described in Ref. [12].
These Gd:SmB\textsubscript{6} samples are insulating to the lowest

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1}
\caption{A 32 MHz SmB\textsubscript{6} oscillator. (a) Representative oscil-
lation outputs at frequencies of 29.6, 30.6, and 32.2 MHz in
ascending order, with dc bias currents of 0.47, 1.56, and 2.42 mA.
Inset shows a false-color electron microscope image of the device
with platinum wires colored in yellow and SmB\textsubscript{6} crystal in white.
The oscillator circuit consists of dc current flowing across the
crystal and a capacitor (either an external capacitor or from the
self-capacitance in SmB\textsubscript{6}) in parallel. An oscilloscope is then
used to measure the output waveform. (b) FFT of the data in (a).
}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{Scaling of frequency with crystal size. (a) Center
frequency of oscillator devices plotted against the crystal surface
area. Insets are images of 29 MHz and 250 Hz devices. The colors
of the markers on this graph match the colors in (b)–(e). (b)–(e)
Output waveforms of the 25 Hz, 250 Hz, 1 kHz, and 29 MHz
devices, respectively. The output of the 32 MHz device is
illustrated in Fig. 1. (f) The range of external capacitance values
we used for each device. No external capacitors are needed for the
two highest frequency (smallest) devices.
}
\end{figure}
Here IS and I0 are surface and total currents through the sample; C is combined internal and external capacitance; G = (RS + RB)/RB, where RS and RB = R0B exp[-Δ/T + Δ/T0] are the surface and bulk resistances with insulating gap Δ; CH = C0H(T/T0)3 and γ are the heat capacity dominated by phonons and heat transfer through external leads with temperature T0, C0H and R0B are heat capacity and bulk resistance in the thermal equilibrium. The detailed analysis of the model is presented in Supplemental Material [20] and here we outline our main results.

In dimensionless units the dynamics of the model depend on four parameters ρB = RB/RS, δ = Δ/T0, Ω = C0H/γCRS = th/TE, and i0 = th/2γRS/S, where th = C0H/τ and TE = RS C are time scales of thermal and electrical processes. The latter two can be easily tuned in the experiment by the dc bias current I0 or capacitance C, and they control the behavior of the model. For the first two we use δ = 18 and ρB = 80, which correspond to a 0.7-mm-sized sample 5 (see Supplemental Material [20], Fig. S3) at T0 = 2 K. The system of Eqs. (1) has only one fixed point (at which IS = 0 and T = 0), which is not allowed to be a saddle one. The regime diagram of the model, presented in Fig. 3(a), has the steady state regime, corresponding to a stable fixed point. The regime is separated by the Hopf bifurcation line from the limit-cycle regime, supporting nonlinear time-dependent oscillations of the current and the temperature and corresponding to an unstable fixed point. Figures 3(b) and 3(c) present the phase curves for the system (1), which illustrates the fate of the unstable fixed point, and the result of its explicit numerical integration. The oscillations, illustrated in Fig. 3(d), can be separated into four phases. (i) Joule heating. The surface current achieves maximum, while temperature is minimum. (ii) Discharging of capacitor. The energy flows from electrical to thermal. (iii) Cooling phase. Energy dissipates to wire leads. The current is minimized, while the temperature is maximized. (iv) Charging of capacitor. The energy flows from thermal to electrical. The system is open and nonequilibrium, but during the second and fourth phases the energy of the system is approximately conserved.

In Fig. 4 we compare the modeling results with experimentally measured oscillation behavior in sample 5. The raw experimental data can be found in the Supplemental Material [20], Fig. S3. As shown in Figs. 4(a) and 4(b), oscillations appear if the capacitance is larger than the minimal value C and only in a finite interval of currents, IC1 < I0 < IC2, which corresponds to conditions i01 < i0 < i02 and Ω < Ω2 in our model (1) according to the regime diagram in Fig. 3(a). Illustrated in Figs. 4(c) and 4(d), between IC1 and IC2 the dependence of the frequency on the current is linear, while the dependence of the amplitude has a bell-shaped dependence. For a fixed dc bias current, the amplitude of the oscillations increases with capacitance until saturation, while the frequency smoothly decreases. The critical values of currents and capacitance differ from sample to sample.
and CH mono gas. Consider a quantum well embedded in undoped quantum well heterostructures with two-dimensional electron gas. Candidate systems are Be

\[ \text{to sample, but the behavior is general for all of them. According to our model, the oscillation frequencies are given by the inverse time scale } t_H^1 \approx t_E^3, \text{ which drastically decreases with sample surface area, in agreement with the experimental trend [Fig. 2(a)].}

While the major focus of this Letter is on oscillators operating at low temperature based on proposed topological Kondo insulator SmB\(_6\), the model developed here, in fact, describes a general system of a semiconductor and a metallic channel thermally and electrically coupled together. It is therefore in principle possible to realize such a tunable oscillator in other materials and at ambient temperatures. Candidate systems are Be\(_2\)Se\(_3\)/Bi\(_2\)Te\(_3\) topological insulators [23,24], or less-exotic semiconductor quantum well heterostructures with two-dimensional electron gas. Consider a quantum well embedded in undoped narrow-band semiconductor InAs sample with length \( l \sim 1 \mu m \), width \( w \sim 1 \mu m \), and height \( h \sim 1 \mu m \). At room temperatures \( T \approx 300 \text{ K} \) undoped InAs has resistivity \( \rho_B = 0.16 \Omega \text{ cm} \), heat capacitance \( C_H^0 = 0.25 \text{ J/}^\circ \text{C} \), heat conductivity \( W = 0.27 \text{ J/(}^\circ \text{C cm s)} \), and density \( \rho_D = 5.62 \text{ g/cm}^3 \). As a result for a typical resistance of two-dimensional electron gas \( R_S = 500 \Omega \), the condition \( R_S \approx R_B \) is satisfied. The parameters of our model, given by Eqs. (1), can be estimated as \( \gamma = Wld/h \approx 27 \times 10^{-6} \text{ J/sK} \) and \( C_H = C_{B_D}ldh \approx 1.3 \times 10^{-6} \text{ J/K} \). The first condition \( \Omega \sim 1 \) is satisfied if the time of thermal processes \( t_H \approx 56 \text{ ns} \) matches the time of electrical processes \( t_E = R_S C \), which can be achieved for a capacitance \( C = 0.1 \text{ nF} \). The second condition, \( i_0 \sim 1 \), is satisfied for electric current \( I_0 \approx \sqrt{\gamma T/R_S} \approx 4 \text{ mA} \). The observation of oscillation in this nanostructure may demand fine-tuning of parameters; nevertheless, we are optimistic that the conditions can be satisfied at room temperature.

This material is based on research sponsored by Air Force Research Laboratory (AFRL) and the Defense Advanced Research Agency (DARPA) under Agreement No. FA8650-13-1-7374.

A. S. and D. K. E. contributed equally to this work.

[1] G. Aeppli and Z. Fisk, Comments Condens. Matter Phys. 16, 155 (1992).
[2] J. C. Cooley, M. C. Aronson, Z. Fisk, and P. C. Canfield, Phys. Rev. Lett. 74, 1629 (1995).
[3] M. Dzero, K. Sun, V. Galitski, and P. Coleman, Phys. Rev. Lett. 104, 106408 (2010).
[4] M. Dzero, K. Sun, P. Coleman, and V. Galitski, Phys. Rev. B 85, 045130 (2012).
[5] M. Dzero, J. Xia, V. Galitski, and P. Coleman, Annu. Rev. Condens. Matter Phys. 7, 249 (2016).
[6] D. J. Kim, S. Thomas, T. Grant, J. Botimer, Z. Fisk, and J. Xia, Sci. Rep. 3, 3150 (2013).
[7] S. Wolgast, C. Kurdak, K. Sun, J. W. Allen, D. J. Kim, and Z. Fisk, Phys. Rev. B 88, 180405 (2013).
[8] M. Neupane, N. Alidoust, S. Y. Xu, T. Kondo, Y. Ishida, D. J. Kim, C. Liu, I. Belopolski, Y. J. Jo, T. R. Chang, H. T. Jeng, T. Durakiewicz, L. Balicas, H. Lin, A. Bansil, S. Shin, Z. Fisk, and M. Z. Hasan, Nat. Commun. 4, 2991 (2013).
[9] N. Xu, X. Shi, P. K. Biswas, C. E. Matt, R. S. Dhaka, Y. Huang, N. C. Plumb, M. Radovic, J. H. Dil, E. Pomjakushina, K. Conder, A. Amato, Z. Salman, D. M. Paul, J. Mesot, H. Ding, and M. Shi, Phys. Rev. B 88, 121102 (2013).
[10] N. Xu et al., Nat. Commun. 5, 4566 (2014).
[11] P. Syers, D. Kim, M. S. Fuhrer, and J. Pagliue, Phys. Rev. Lett. 114, 096601 (2015).
[12] D. J. Kim, J. Xia, and Z. Fisk, Nat. Mater. 13, 466 (2014).
[13] G. Li, Z. Xiang, F. Yu, T. Asaba, B. Lawson, P. Cai, C. Tinsman, A. Berkley, S. Wolgast, Y. S. Eo, D.-J. Kim, C. Kurdak, J. W. Allen, K. Sun, X. H. Chen, Y. Y. Wang, Z. Fisk, and L. Li, Science 346, 1208 (2014).
[14] B. S. Tan, Y.-T. Hsu, B. Zeng, M. C. Hatnean, N. Harrison, Z. Zhu, M. Hartstein, M. Kiourlappou, A. Srivastava, M. D. Johannes, T. P. Murphy, J.-H. Park, L. Balicas, G. G. Lonzarich, G. Galakrishnan, and S. E. Sebastian, Science 349, 287 (2015).
[15] V. Alexandrov, P. Coleman, and O. Ertiry, Phys. Rev. Lett. 114, 177202 (2015).
[16] D. K. Efimkin and V. Galitski, Phys. Rev. B 90, 081113 (2014).
[17] J. Iaconis and L. Balents, Phys. Rev. B 91, 245127 (2015).
[18] P. Nikolovic, Phys. Rev. B 90, 235107 (2014).
[19] D. J. Kim, T. Grant, and Z. Fisk, Phys. Rev. Lett. 109, 096601 (2012).
[20] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.116.166603 for device
fabrication, detailed analysis of the model, additional raw data plots, and control samples.

[21] M. F. Hundley, P. C. Canfield, J. D. Thompson, Z. Fisk, and J. M. Lawrence, Phys. Rev. B 42, 6842 (1990).

[22] J. C. Cooley, M. C. Aronson, and P. C. Canfield, Phys. Rev. B 55, 7533 (1997).

[23] X.-L. Qi and S.-C. Zhang, Rev. Mod. Phys. 83, 1057 (2011).

[24] M. Z. Hasan and C. L. Kane, Rev. Mod. Phys. 82, 3045 (2010).