Response to "Comment on 'Fundamental limits of energy dissipation in charge-based computing' " [Appl. Phys. Lett. 98, 096101 (2011)]

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Zhirnov, Cavin, and co-workers (ZC) presented in Ref. 1 an analysis of the fundamental limits of a binary switch, represented by a double well system, which purported to show that such a switch must dissipate $k_BT \log(2)$ because the switching event must dissipate an energy equal to the barrier height.

We showed in Ref. 2 that their argument was incorrect because by switching the system smoothly using the adiabatic paradigm of Landauer and Bennett,[3] dissipation much lower than $k_BT \log(2)$ could be achieved. The barrier height must indeed be much larger than $k_BT \log(2)$ when the device holds a bit of information but can be lowered in the switching process in such a way that much less energy needs to be dissipated.

ZC argued in Refs. 4 and 5 that the apparent energy saved by adiabatic switching would in fact be dissipated in the electrodes that create the adiabatically changing barriers. In an argument in Ref. 5, invoking "Cavin's demon" to charge a capacitor, they claimed that even smoothly (adiabatically) charging and discharging the capacitance representing the barrier-created electrodes would inevitably dissipate more than $k_BT \log(2)$. Because Landauer's principle (LP) clearly contradicts this, they argue in Ref. 5 that LP only applies to "hypothetical" systems that are "perfectly isolated from the external environment."

Our results in Ref. 6 show by direct measurement that a capacitor can in fact be charged and discharged adiabatically. The energy stored on the capacitor can be much larger than $k_BT \log(2)$ while the dissipated energy is much less than $k_BT \log(2)$. This precisely contradicts the "Cavin's demon" argument of Ref. 5 and supports LP.

To argue as they do in their Comment[7] that this is somehow off-point because it focuses on charging and discharging a capacitor is incorrect. We quote their paper[5] (third page) as follows:

> Thus, operation of all charge transport devices includes charging/discharging capacitances to change barrier height controlling charge transport. This applies to all devices including FET, RTD, SET, QCA, etc. In all cases the binary transitions are promoted by *barrier deformations* (e.g. changes in barrier height, width or shape) that always involve charging or discharging of a *control capacitor* (e.g. a gate capacitor Cg in the case of FET). <u>Thus, the energy to "*deform*" the barrier is equivalent to the energy of charging the control capacitor.</u> (Italics and underlining in original.)

Furthermore, their claim that our paper addresses smooth raising and lowering of barriers while their analysis applies only to the case of devices that "switch very rapidly to a new state" is incorrect. The text of the "Cavin's demon" critique of adiabatic switching refers to "a slow decrease of the control barrier,"[5] and additional details of their calculation for a voltage ramp applied to an *RC* circuit are given in Ref. 8 where they state on page six "The energy dissipated in *RC* circuit by adiabatic charging cannot be smaller than kT ln 2." Their argument and our experiment are clearly focused on the same issue.

It is disingenuous for them to claim that their critique has been for all physical systems and not aimed at electric charge. The introduction to Ref. 5 states that it aims to "review the limits of adiabatic switching for *electron* transport devices," later listing examples as "FET, RTD, SET, QCA, etc." (page 3). Reference 9 summarizes the import of their analysis in Ref. 1 by saying "the search for alternative logic devices should embrace the concept of using state variables other than electric charge."

In our letter[6] we did not address issues of the power dissipation in the signal generator, choosing instead to focus on an experimental test of ZC's clear assertion of a dissipation limit in adiabatic charging.[5,8] The clock generators are not fundamental to the issue at hand. Resonant circuits can address the issue of recycling energy in the clock signals.

It was not our goal in Ref. 6 to show how adiabatic switching could be employed in specific systems; we have done that elsewhere.[2] Our goal in Ref. 6 was to address specific claims made by ZC regarding fundamental limits of dissipation in charge-based devices.

[1]V. V. Zhirnov, R. K. Cavin, J. A. Hutchby, and G. I. Bourianoff, Proc. IEEE **91**, 1934 (2003).
[2]C. S. Lent, M. Liu, and Y. H. Lu, Nanotechnology **17**, 4240 (2006).
[3]R. W. Keyes and R. Landauer, IBM J. Res. Dev. **14**, 152 (1970); R. Landauer, *ibid.* **5**, 183 (1961); C. H. Bennett, *ibid.* **17**, 525 (1973).
[4]V. V. Zhirnov and R. K. Cavin, Nanotechnology **18**, 298001 (2007) See also response in C. S. Lent, *ibid.* **18**, 298002 (2007).
[5]R. K. Cavin, V. V. Zhirnov, J. A. Hutchby, and G. I. Bourianoff, Fluct Noise Lett. **5**, C29 (2005).
[6]G. P. Boechler, J. M. Whitney, C. S. Lent, A. O. Orlov, and G. L. Snider, Appl. Phys. Lett. **97**, 103502 (2010).
[7]V. V. Zhirnov and R. K. Cavin, Appl. Phys. Lett. **98**, 096101 (2011).
[8]R. K. Cavin, V. V. Zhirnov, J. A. Hutchby, and G. I. Bourianoff, Proc. SPIE **5844**, 1 (2005).
[9]J. A. Hutchby, G. I. Bourianoff, V. V. Zhirnov, and J. E. Brewer, IEEE Circuits Devices Mag. **21**, 47 (2005).

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