The memristor and the scientific method

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Abstract— **In 1971 a "missing memristor" was proposed by a circuit theorist named Leon Chua as a 4th fundamental passive circuit element defined by a non-linear relationship between electric charge and magnetic flux linkage. In 2008 a research group from Hewlett-Packard led by Stan Williams claimed credit for finding this "missing memristor" based on the observation of a zero-crossing hysteresis effect. I recently proved that the zero-crossing hysteresis effect can be produced by dynamic systems other than the memristor or more generalized memristive systems. In light of this development I address several public comments made by Stan Williams regarding the history of the memristor.**

Keywords- scientific method, memristor, RRAM, ReRAM

I. INTRODUCTION

Advancements in science are not made based on whether large corporations or famous scientists endorse a particular theory or idea. Science progresses solely based upon the formulation, testing, and modification of hypothesis. That is the scientific method.

Corporations have a profit motive and scientists, while typically portrayed as seekers of objective truth, can have their judgments clouded by a desire to enhance their reputations.

The "memristor" was originally proposed in 1971 by Leon Chua as a missing fourth fundamental circuit element linking magnetic flux and electric charge [1]. In 2008 a group of scientists from HP led by Stan Williams claimed to have discovered this missing memristor [2]. It is my position that HP's "memristor" claim lacks any scientific merit.

My position is not that the HP researchers have presented an incorrect model of a memristor or even an incorrect model of resistance memory. If this were the case it would not be so bad because an incorrect model could at least be proven incorrect and possibly corrected to produce a better model. My position is that the HP researchers have avoided presenting any scientifically testable model at all by hiding behind the reputation of Leon Chua and the mythology of the memristor. They have thus attempted to bypass the principle of the scientific method.

If the HP researchers had developed a realistic model for resistive memory (whether it is called "memristor" or by some other name) it could be vetted by other researchers, compared to experimental data, and determined to be true or false. If necessary the model could be modified or corrected and an improved version of the model could be produced.

This is not what has happened.

Instead the HP researchers presented the discovery of the "missing memristor" predicted by Leon Chua in 1971. The HP researchers wrote down equations in the form suggested by Leon Chua and produced several zero-crossing hysteresis curves based on their memristor equations. The HP researchers pointed out that a similar zero-crossing hysteresis curve is produced by resistance switching in thin films of TiO_2 and declared that based on this similarity they had discovered the fourth fundamental passive circuit element.

The problem is that the memristor equations presented by the HP researchers have very little to do with the actual physics of TiO_2 thin films. Phenomena such as non-linear ion drift, filament formation, redox reactions, electron tunneling, phase change, and numerous other effects associated with resistance switching physics of thin films were all completely ignored. Instead "window functions" were introduced to treat any discrepancy between HP's memristor equations and experimental data.

Now, almost 4 years later, there is still no evident improvement of any of the so-called "memristor" models of the HP researchers which can be tested by the scientific method. Instead Stan Williams (in collaboration with Leon Chua) have convinced other researchers to change the original definition of memristor so as to cover all known 2-terminal resistance memory devices exhibiting a pinched hysteresis curve. I recently proved that, even given the new definition of a memristor, the assertions of Leon Chua and Stan Williams are false [3].

This article addresses several public comments made by Stan Williams of Hewlett-Packard regarding the history of the memristor available at

http://regmedia.co.uk/2011/12/22/hp_memristor_history.pdf

II. RESPONSES TO THE COMMENTS OF STAN WILLIAMS OF HEWLETT-PACKARD

Page 1, paragraphs 1 and 2:

Stan Williams begins by giving a biography of Leon Chua and listing his accomplishments. It is acknowledged that Leon Chua is a famous circuit theorist with many achievements. However, this does not provide evidence that Chua's idea of a memristor is correct.

Throughout human history famous scientists have had theories which, while being accepted in their day, later turned out to be wrong or misguided. One of the world's first famous scientists was the ancient Greek philosopher Aristotle who had several ideas about the physical world including the idea that the world could be divided into the four elements of earth, air, fire, and water. The ideas of Aristotle shaped the world for almost 1800 years but were unfortunately poorly formulated and did not follow the scientific method. It was not until the renaissance and the coming of Galileo and Newton that many of Aristotle's ideas were shown to be incorrect based on the modern application of the scientific method.

In a more recent example in 1989 the chemists Martin Fleischmann and B.Stanley Pons went to the press with an amazing discovery of a new type of fusion [4]. Unfortunately these chemists did not properly apply the scientific method to their claims prior to making their pronouncements to the press. Their claims were then very publically debunked. This has resulted in reluctance to fund research in this area of energy science which may be a bad thing considering that there might be some commercial use for a new form of fusion. If there had been a better adherence to the scientific method this may have been prevented.

Page 1, paragraph 3:

Stan Williams describes memristive systems as a generalization of the memristor which was described in a 1976 publication by Chua and Kang [5]. Williams comments that

"..it is relatively 'easy to show' that if both R and f are independent of the current i, the two equations reduce to the original definition of a memristor."

This statement appears to demonstrate a very poor understanding of memristive (and dynamic) systems. In the case described by Williams where R and f are independent of the current i the memristive system reduces to (1).

$$\begin{gathered} v(t) = R(\boldsymbol{w})i(t) \\ \frac{d\boldsymbol{w}(t)}{dt} = f(\boldsymbol{w}) \end{gathered} \tag{1}$$

Since the dynamic equation is only a function of the state $\boldsymbol{w}$ this system is a volatile, memoryless system representative of a time-dependent resistor. This case cannot be a memristor because it has no memory. A correct dynamic system model for a memristor requires a linear relationship between the rate of change of the state and the current as in (2).

$$\begin{gathered} v(t) = R(\boldsymbol{w})i(t) \\ \frac{d\boldsymbol{w}(t)}{dt} = i(t) \end{gathered} \tag{2}$$

I pointed this out at the 2010 IEEE Symposium on Circuits and Systems [6] and Chua noted this in Eq. 29a and 29b of [7]. Thus this statement of Williams seems to indicate a misunderstanding of memristive systems.

Page 2, paragraph 1:

Stan Williams summarizes the 1976 paper of Chua and Kang by stating

"The key result was that any electronic circuit element that displayed a pinched hysteresis loop in its current-voltage characteristic could be described mathematically by the two memristive systems equations."

I have recently provided several examples of dynamic systems falling outside of the definition of memristive systems that also produce zero-crossing hysteresis curves [3]. My paper establishes that it is possible that neither the memristor nor memristive systems have anything to do with the zero-crossing hysteresis curves found in the Lissajous curves of RRAM devices.

Page 2, paragraph 2:

Stan Williams explains why the term memristor has been used in place of the more generic memristive systems.

"Chua has recommended that the nomenclature be simplified by referring to both as memristors, since in fact the generalization was a 'trivial extension'"

This comment directly contradicts the following statement in the first paragraph of Chua's 1976 paper [5] which introduced memristive systems.

"..there remains an even broader class of physical devices and systems whose characteristics resemble those of a memristor and yet cannot be realistically modeled by this element,.."

It is difficult to see how something that previously "cannot be realistically modeled" is all of a sudden "a trivial extension."

Page 2, paragraph 4:

Stan Williams argues that

"Examples of memristors include bipolar and unipolar resistive switches, often called RRAM or ReRAM; 'atomic switches'; spin-torque transfer RAM devices, phase change memory devices, and several other systems based on a wide variety of materials and mechanisms.."

There is no definitive evidence that either the memristor or memristive systems provide a correct framework to model any of these materials. Pershin and Di Ventra reviewed a variety of models for different memory types formulated in terms of memristive systems [8]. However, just as in the case of HP's 2008 memristor article [2], there has not yet been adequate experimental evidence to determine whether these models are correct or not.

Even if memristive systems models are found to be useful in RRAM modeling it is faulty logic to call all these devices memristors. The logic used by Chua and Williams is that since a memristor generates a zero-crossing hysteresis curve and memristive systems generate zero-crossing hysteresis curves it is okay to call all memristive systems a memristor. Under this type of sloppy logic since a human is a mammal and dogs, whales, and elephants are all mammals then dogs, whales, and elephants should all be considered humans.

In any case I proved that non-memristive systems can produce zero-crossing hysteresis [3] and the Biolek group proved that it is impossible for type II zero-crossing hysteresis curves (usually associated with unipolar memory) to represent memristors [9]. Thus calling devices that exhibit zero-crossing hysteresis "memristors" is scientifically meaningless without stronger experimental evidence supported by a memristor model.

Page 2, paragraph 5:

Stan Williams addresses the question of whether the memristor should or should not be considered a fourth fundamental circuit element by commenting

"We will see how the textbooks choose to define it."

If the memristor is a genuine scientific concept this should not be left up to the popular opinion of textbook writers. However, even Pershin and Di Ventra, who have been two of the most active researchers in memristive theory besides Chua comment that they *"..prefer to subscribe to the notion that there are only three fundamental circuit elements-resistors, capacitors and inductors, with or without memory."* (Section II.H of [8])

Williams states that:

"Chua has shown mathematically that it is not possible to construct an equivalent circuit for a memristor using any combination of only passive nonlinear resistors, capacitors and inductors."

This is true but it is also impossible to construct an equivalent circuit for a diode (or other non-linear circuit element) using linear resistors, capacitors, and inductors. Does this mean that diodes should be considered as "fundamental?" No. A diode is one example of a non-linear generalization of resistors and the memristor is one example (NOT THE ONLY EXAMPLE) of a dynamic system generalization of a resistor. Similarly capacitors and inductors can be generalized to dynamic mem-capacitors and mem-inductors as shown by Pershin and DiVentra [8] and transistors can be generalized to dynamic mem-transistors which I discussed at ICECS 2010 [10].

<u>Page 3, paragraph 3:</u>

On the subject of who discovered the memristor Stan Williams comments

"The memristor as a mathematical model or entity was discovered and made rigorous by Leon Chua."

I contest the "rigor" of Chua's memristor as a mathematical model given the loose definition in which all zero-crossing hysteresis curves represent a memristor (which I recently disproved [3]). It is notable that in 1960 Bernard Widrow coined the term memistor (memory resistor) as a device defined by charge dependent conductance [11]. Widrow used memistors as a component to simulate electronic neurons. The differences between Widrow's and Chua's memory resistors are that Widrow's memistor was a 3-terminal device and real while Chua's memristor was a 2-terminal device conceived ten years after Widrow's memistor and theoretical.

<u>Page 3, paragraph 4:</u>

On the subject of other useful mathematical models for resistance memory Stan Williams remarks

"We are not aware of any useful mathematical models presented in any of these previous works for predicting the behavior of these devices in an electronic circuit."

In 1970 a review article on resistance switching in amorphous oxides [12] commented that there were as many theories as there were researchers in the field. Perhaps it is questionable whether these models were "useful" or correct but there is a lack of evidence that HP's memristor models are any more useful or correct.

"We are not aware that any of these researchers cite Chua's papers after they appeared in print."

Based on [12] and another 1973 review article on chalcogenide memory resistors [13] there were at least 100-200 researchers in this field during the time of Chua's papers. The memristive systems article [5] was featured in the Proceedings of the IEEE so it is very likely that many of the researchers in memory resistors were at least peripherally aware of this article. The reason that none of these researchers cited Chua's papers may not be that the researchers were unaware of the articles but rather that Chua's papers were viewed as useless. This view may still be correct.

It is also notable that in at least one diligent U.S. Patent Examiner did cite Chua's memristor paper in the examination of a patent by Stanford Ovshinsky issue in 2006 [14].

"..Chua was not aware of these studies.."

In [1] Chua cites Ovshinsky's 1967 work on reversible electrical switching phenomena in disordered structures which served as a precursor to modern phase change memory. Since Chua was aware of Ovshinsky's research it is curious why he did not pursue this avenue and attempt to find examples of his so-called missing memristor.

<u>Page 4, paragraph 1:</u>

Stan Williams comments on the subject of the connection between memristive (dynamic) systems and resistance switching phenomena that

"There were no pointers across this disciplinary divide."

State-space dynamic systems is routinely taught in the graduate and advanced undergraduate Electrical Engineering curriculum in courses covering Modern Control Systems or Signal Processing. It is true that non-linear dynamic systems models are not typically used for the analysis of fundamental circuit components but there were already some precedents from the 1990's such as non-linear dynamic circuit models developed for the sub-threshold operation of a synaptic transistor [15].

Page 4, paragraph 2:

"In our papers, we cite those papers that appeared earliest and those that we have found most useful to our research."

It is notably suspicious that Argall [16] was not cited in HP's early memristor papers since in 1967 Argall disclosed the same material (TiO_2), illustrates the same zero-crossing hysteresis curve, and uses the exact same value of mobility ($10^{-10}cm^2/Vs$) as in [2]. One difference is that Argall attributes this mobility to electronic rather than ionic conduction. It is difficult to imagine what possible motivation the HP researchers had in excluding this reference since it is clearly closer than any other of the cited references. Perhaps it was to avoid having to disclose this reference to the U.S. Patent Office as prior art which would have made it more difficult to get their patents issued.

Page 4, paragraph 3:

Stan Williams states that the memristor is:

"..a rigorous mathematical model that can be used to predict the behavior of a wide variety of physical devices."

Is Williams talking about the memristor as defined in 1971 [1] or the memristor as re-defined by Chua in 2011 [7]? Exactly how "rigorous" is the memristor as a mathematical concept if it can be redefined so easily. Imagine that the scientists at CERN suddenly decided to mathematically redefine the theoretical Higgs boson because they found a particle that had some similar characteristics to the Higgs boson but was not quite right. I do not think this would be acceptable science and I do not see why it should be acceptable in the case of Chua's memristor.

Page 4, paragraph 4:

"HP has a large experience base and IP portfolio in this general area of memory devices."

I worked as a Patent Examiner for the U.S. Patent & Trademark Office from 2000-2005 during which time I helped organize the patent classification for nanotechnology. I also published a paper in a nanotechnology business journal in 2010 based on a review of RRAM and phase change memory patents [17]. So I know a little bit about patents in general and memory resistor patents specifically.

HP's memory resistor IP portfolio is mostly concentrated on molecular materials and nanowire crossbar structures. Since 2006 HP has gradually began shifting their patents to focus on thin film materials rather than molecular memory but this is only after other companies including Micron, Sharp, Samsung, and Unity Semiconductor had already began focusing on thin film chalcogenides and metal oxide materials. Most of HP's recent patent applications use the term "memristor" or "memristive" in the patent claims which may be a motive for trying to get this term accepted as a universal term for 2-terminal resistance memory.

I recently updated the US patent data from my 2010 article [18] up until January 1, 2012 and the data indicates that for metal oxide memory resistors the top patent holders are Sharp, Samsung, Unity Semiconductor, Panasonic, and Toshiba. HP is #6 overall in total patent count but many of their issued patents have claims limited in scope to molecular materials. Hynix Semiconductor is #13 on the list but most of their patents are limited to phase change materials. A business motive may thus exist for HP to change the definition of memristor to include phase change memory.

Over the past few years I have been filing prior art with the U.S. Patent and Trademark Office (as allowed under 37 CFR 1.501) in cases where I believe there was a mistake made in issuing patents related to memory resistors. It is my view that several of what may be considered HP's basic "memristor" patents clearly fail to meet the criteria of 35 USC 102 (novelty) and 35 USC 103 (non-obviousness) when compared to earlier work of other inventors from competing companies. I am currently in the process of having these "memristor" patents of HP revoked or amended under the ex parte reexamination procedure as provided by US regulations (37 CFR 1.510).

"We finally decided that molecules were not robust enough for applications and concentrated on inorganic systems."

It seems convenient that this decision coincides with the developments of metal oxide RRAM achieved by other companies. One patent of particular interest in relation to HP's "memristor" was issued to researchers working for Samsung [19] based on legitimate science on the role of oxygen ion drift in bi-layer metal oxide thin films [20]. There are several suspicious similarities between Samsung's patent and HP's alleged memristor. For example paragraph [0061] of Samsung's patent application reads *"If a positive (+) voltage is applied from 0V to M2 through the upper electrode, then oxygen ions may move from the titanium dioxide (TiO_2) of the first oxide layer toward the upper electrode, lowering the resistance state of the first oxide layer as if the first oxide layer is formed of TiO or Ti_2O_3 instead of TiO_2."*

In addition to this I have noticed some cases where HP has appeared to copy patented ideas from other companies, such as the CMOx and tunneling oxide concepts of Unity Semiconductor. Relabeling of other people's technology with a new name and then issuing a press release to take credit is not innovation.

It is notable that Williams does have a patent application with priority going back to Oct. 3, 2006 which is the first to mention the memristor [21]. However, based on this patent application Williams appeared unsure at this time of the role of molecular structures in the device (see paragraphs [0029], [0042], [0045], [0046], [0056], [0061], [0065], [0076] of the patent application).

It appears to me that it is likely that the similarity between Williams' patent application and the work of the researchers from Samsung might be a coincidence unless HP had an internal contact within Samsung or within the Korean patent office. The reason is that Samsung's patent application was only publically available in the US as of Aug. 30, 2007 almost a year after Williams' patent priority. However, Samsung's patent application has foreign priority going back to Feb. 27, 2006. Nevertheless at the time of the 2008 Nature article [2] it is possible that Williams or others from HP could have become aware of the Samsung patent application and adjusted their position accordingly to exclude molecular switching effects.

"The big breakthrough, and our most significant contribution, came in 2006 when we realized that the time derivative of the state variable in Chua's dynamical state equation was comparable to the drift velocity of oxygen vacancies in a titanium dioxide resistance switch.."

I do acknowledge it may be useful in some cases to have dynamic systems models for memory resistors (particularly for device applications involving signal processing and control systems). However, as I have shown in [3], it is possible to generate zero-crossing hysteresis with non-memristive models. There is as yet no definitive proof that any of HP's memristor or memristive systems models based on oxygen vacancy drift provide a valid or useful model for the observed memory resistance effects of TiO_2 or any other material. Numerous other explanations involving electron tunneling effects, phase change phenomena, redox reactions, etc. are possible. While dynamic systems representations may be formed for these other cases there is no evidence that the memristive systems formulation of Chua is the optimum representation. This issue is confounded by the encouragement of the HP researchers to use "window functions" which hide any discrepancy between memristive models and experimental results.

<u>Page 4, paragraph 5:</u>

"Any mechanism that is mathematically consistent with Chua's equations defines a memristor."

Stan Williams cites two papers as examples of "mathematically consistent" with Chua's equations. The first paper [22] is based on an ionic drift-diffusion model and includes simulation results. However, there is no experimental evidence providing a comparison to the simulation results which would be necessary to determine the accuracy and usefulness of the model. Correct application of the scientific method requires the comparison with experimental data before the claim of the drift-diffusion memristive model is considered correct. Instead window functions are often mentioned in the literature to correct any deficiency with experimental results.

The second paper [23] does include experimental data but presents a dynamic model based on curve fitting rather than a predictive model. In this paper the dynamic systems equations are not defined at $i=0$ and are only piecewise continuous between off switching ($i>0$) and on switching ($i<0$). This is not mathematically consistent with Chua's memristor definition and is unrealistic because it would lead to the conclusion of an infinite retention time.

Page 5, paragraph 1:

"..it is the peer review system that keeps the system in balance - any paper submitted will most likely be reviewed by your most critical competitor, so what finally appears in print has been vetted thoroughly."

One of these thoroughly vetted memristor papers led to enough misinformation that other researchers had to publish a paper to correct the misinformation [24].

"..our papers have been cited over 1000 times by other researchers in the field"

I suspect that this could be a sociological phenomenon rather than a reflection of the intrinsic value of the memristor or memristor models as a scientific concept. Academic researchers determine their career based on reputation and reputation is often enhanced by association with famous people. Thus, when a well-known scientist working for one of the most well-known companies in the world endorses the theory of a well-known circuit theorist this will attract many academic researchers.

Considering that there was already much research underway in RRAM prior to [2] it was not difficult for many researchers to re-label their work as a memristor. The problem is that most of the researchers did not properly understand the 1971 definition of a memristor given by Chua or the 1976 definition of memristive systems by Chua and Kang. These researchers may have confused other dynamic systems with memristors. Chua probably should have stepped in to correct researchers who were incorrectly using the term memristor but his judgment may have been clouded by the desire to obtain a status of scientific immortality as the discoverer of the alleged fourth fundamental passive circuit element.

Perhaps a better indication of the intrinsic value of HP's memristor models can be determined by the number of industry scientists and engineers outside of HP who have adopted the memristor as a working model to design and manufacture RRAM. Those who work in industry do not have the same pressure to publish papers as those in academia and are more likely to value the practical merits of any model over mythological allegories. During the most recent IEDM meeting in Washington D.C. last December there were numerous presentations on RRAM from researchers working for Samsung, Macronix, Panasonic, and other companies but not a single one of these researchers was using a memristor model or even cited any of the 1000+ memristor papers. Meanwhile researchers from Hynix Semiconductor (the alleged partner of HP in memristor development) gave a presentation focused on phase change memory and did not mention the memristor or their association with HP. If the memristor were truly a legitimate model for RRAM it is difficult for me to understand why industry scientists outside of HP would not be adopting it after almost four years

III. CONCLUSION

This paper attempts to demonstrate that various public statements made by Stan Williams of Hewlett-Packard regarding the "missing memristor" lack scientific support. The following facts are clear:

1) Leon Chua contradicted his own definition of the memristor between his 1976 and 2011 papers. It is suspicious that the memristor had a very specific definition for 40 years and only 3 years after HP

announced that they had discovered this missing memristor the definition was deliberately changed. This would not be allowed for other theoretical scientific concepts such as the Higgs boson.

2) Stan Williams and Hewlett-Packard have used the new definition to publicly claim that all 2-terminal resistance memory including all forms of RRAM, phase change memory, and MRAM are memristors without providing sufficient scientific support for these claims. It is suspicious for HP to do so when there are several other companies developing alternative forms of RRAM, phase change memory, and MRAM which may compete with the TiO_2 "memristor" of Hewlett-Packard.

3) I have proven [3] that it is possible to construct zero-crossing hysteresis curves using dynamic systems other than that of the memristor or memristive systems. This disproves the "key result" (as claimed by Williams) of Chua and Kang's 1976 paper.

Perhaps the statements of Chua and Williams regarding the "missing memristor" are simply a product of self-delusion or overenthusiasm for their own research rather than part of a deliberate business plan by HP to advance a corporate agenda. However, it is also representative of sloppy science introducing much misinformation into the scientific community which is being accepted as gospel by numerous naïve researchers and science reporters. This type of behavior should not be tolerated from any scientist no matter how well-respected or influential.

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