Carbon 119 (2017) 573–577

Contents lists available at ScienceDirect

Carbon

journal homepage: www.elsevier.com/locate/carbon

Mildred S. Dresselhaus (1930 – 2017) – A Tribute from the Carbon Journal

The international carbon community has seen the passing of one of its most accomplished and beloved members, Professor Mildred S. Dresselhaus. Millie had a close connection to the *Carbon* journal as a member of its Honorary Advisory Board, a frequent attendee and invited speaker at the annual carbon conference series, a winner of the American Carbon Society Medal - its highest honor, and collaborator and mentor to a number of scientists on our editorial team. With such contributions and connections, there is no question that the journal would want to publish a tribute.

We are not alone, however, in our desire to honor Professor Dresselhaus. Her achievements and fame extend beyond the normal bounds of our community to include such distinctions as the Kavli Prize for Nanoscience, the Presidential Medal of Freedom conferred by Barack Obama, and her status as the first ever female full professor at MIT. Her life and career served as an inspiration to many both inside and outside the carbon materials community. Obituaries and tributes are being published by other journals and societies, and stories have appeared in the New York Times and on National Public Radio. I recently saw her featured in a General Electric television advertisement focused on women in technical careers, asking "What if Millie Dresselhaus, female scientist, was treated like a celebrity?". Well here at *Carbon*, and in the larger world of science, she very much is.

With all of this coverage, what can we add that has not already been said? The *Carbon* group has therefore decided to publish a tribute of a more personal nature, contributed by people formally connected to the journal who knew and worked with Millie over the years. What follows are short personal narratives contributed by D.D.L. Chung, *Carbon* editorial board member and Dresselhaus Ph.D. graduate; Mauricio Terrones, *Carbon* editor and collaborator, Katsumi Kaneko, *Carbon* board member and collaborator, Peter Thrower, *Carbon* Editor-in- Chief Emeritus, Morinobu Endo, *Carbon* Honorary Advisory Board Member and collaborator, Hui-Ming Cheng, former *Carbon* editor and visiting scholar in the Dresselhaus laboratory, and Michael Strano, *Carbon* editor and current Dresselhaus colleague at MIT.

For myself, I had admired her work for years through her invited lectures at the annual carbon conferences, but really got to know her as a person just at the end - in the summer of 2016 at the Nobel Laureates' and Medalists' Roundtable event organized by Ljubisa Radovic and Mauricio Terrones (see photo). As a moderator, I spent time with Millie throughout the week-long meeting, and heard her life story, including anecdotes about stepping over drunken sailors on the way to school in her port neighborhood in New York City, and throughout the week was lucky to have this last chance to hear her free flow of ideas on science, politics, and careers. On the panel itself, even among that elite company, Millie stood out as a bright light – an irrepressible personality with something insightful to say on every question. She had an extraordinary enthusiasm for science and for life and will be missed by many in the international carbon community.

- Robert Hurt, Editor-in-Chief

Mildred Dresselhaus in the summer of 2016 at the Medalists Roundtable held in connection with the annual carbon conference at Penn State. Group photo, left to right: Ljubisa Radovic (organizer), Konstantin Novoselov (panelist), Peter Thrower (moderator), Mauricio Terrones (organizer), Mildred Dresselhaus (panelist), Robert Curl (panelist), Don Bethune (panelist), Morinubu Endo (panelist), Robert Hurt (moderator).

http://dx.doi.org/10.1016/j.carbon.2017.04.057
0008-6223

D.D.L. Chung, University of Buffalo

Mildred S. Dresselhaus (fondly addressed as "Millie" by her students and colleagues) is internationally known as "the Queen of Carbon Science". She is noted for her work on graphite, graphite intercalation compounds, fullerenes, carbon nanotubes, graphene and low-dimensional thermoelectrics. Her work emphasized the electronic and optical behavior of carbon nanostructures.

According to the Web of Science (viewed on March 4, 2017), Dresselhaus has 1081 publications, 83167 citations (excluding self-citations) and h-factor 133. Even in 2016 (the last complete year of her life), she has 30 publications and almost 8000 citations. Her authored books include (i) *Raman Spectroscopy in Graphene Related Systems* Wiley, 2011, (ii) *Graphite Fibers and Filaments* Springer, 2011, and (iii) *Thermoelectricity: Thermoelectric and Thermomagnetic Properties in Low-dimensional and Nanoscale Materials*", Springer, 2010.

Dresselhaus was awarded the U.S. Presidential Medal of Freedom in 2014, the U.S. National Medal of Science in 1990, the Enrico Fermi Award in 2012, the $1 million Kavli Prize in Nanoscience in 2012, the von Hippel award in 2013, the Buckley Condensed Matter Prize in 2008, the Oersted Medal in 2008, the Medal of Achievement in Carbon Science and Technology from the American Carbon Society in 2001, etc. In addition, she received honorary doctorate degrees from a large number of universities, which include Harvard and Princeton.

Dresselhaus has shepherded more than 60 Ph.D. students during her 50 years (1967−2017) on the faculty of MIT, where she last served as Institute Professor (the first female attaining this rank in MIT) and was on the faculty of both Department of Electrical Engineering and Computer Science and Department of Physics. I met Dresselhaus in 1973 as a student in her MIT graduate course on solid state physics. I loved the course so much that I decided to do research under her. She was the person that introduced me to carbon science. I was her first graduate student in the field of graphite intercalation compounds. My Ph.D. thesis under her supervision was completed in 1977, a date which she remembered even decades afterward. She was the person that originated my professional name "D.D.L. Chung", which differs from my commonly used name "Deborah Chung". In 2010, in connection with her 80th birthday celebration, I learned that I was her first female Ph.D. thesis student. Below is a private communication from Dresselhaus to me in 2014.

"Deborah:

Your thesis work is historical for me as an early work on a single layer graphene layer where intercalants were used separate the layers. My nanoscience efforts went from graphite intercalation compounds to fullerenes after their discovery and this led to the idea of stretching out fullerenes from C_{60} to C_{70} to … C_{100} and perhaps making a tube that would be a single layer of carbon atoms in thickness. I posed this question to Fujita and Saito when they came to spend a year working with me in 1992, and as a result of their physical model and their tight binding calculations, we wrote a paper on this topic predicting that such a tube could have either semiconducting or metallic properties depending on the orientation of the hexagons made by the sp^2 carbon-bonded atoms along the cylinder. This paper led to the carbon nanotube work that you and others have contributed to. Our group has continued working in the field of nanotubes, and our recent focus is on double-wall and triple-wall nanotubes. Here we use model systems for studying intertube interactions and the importance of tube diameter and metallicity.

We have been studying graphene also as a model system. Here we have worked with Martin Kalbac using C_{13} vs. C_{12} as a probe to distinguish between electronic effects and lattice vibrational effects. We are also here working on few-layer transition metal dichalcogenides and phosphorene, which is our latest new research direction."

Dresselhaus also worked hard serving the research community. She was the Director of the Office of Science at the U.S. Department of Energy (2000−2001), the Chair of the governing board of the American Institute of Physics (2003−2008), President of the American Physical Society, President of the American Association for the Advancement of Science, and Treasurer of the National Academy of Sciences. She worked so hard in reviewing manuscripts for journals that she did this even while travelling.

Dresselhaus was born in New York, NY, in 1930, and spent her childhood in a dangerous, low-income part of New York City. Her parents were recent Jewish immigrants from Poland. She had only one set of clothing, but her mother washed it every day. As a child, she bought old issues of National Geographic. These issues helped nurture her interest in science. She played the violin regularly, even at age 86. As a pianist, I played with her family of string musicians while I was her student at MIT. I remember her cooking and her driving me back to my dorm at the end of the musical evening. Dresselhaus received her B.S. degree from Hunter College in 1951 and her Ph.D. degree from University of Chicago (under the tutelage of Nobel laureate Enrico Fermi) in 1958.

Dresselhaus passed away on Feb. 20, 2017 after a 2-week illness. She was professionally active until the 2-week hospitalization. She is survived by her husband, Gene (married in 1958), her four children (Marianne, Carl, Paul and Eliot), her five grandchildren and her many students, for whom she deeply cared.

At age 85, Dresselhaus attended the International Carbon Conference in State College, PA, in July 2016. In spite of her vast knowledge, she took detailed and neat handwritten notes at essentially every talk that she attended. Her zeal for knowledge is unparalleled. She will remain my role model and continue to inspire me as I strive to follow her footsteps.

Mauricio Terrones, Pennsylvania State University

Millie Dresselhaus is an inspiration for women, young and mature scientists. Her energy, commitment to science and service were unique. She touched and changed the life of numerous people in different aspects. Her departure constitutes a big loss for science and for humanity; she is irreplaceable! Millie was energetic, knowledgeable, cunning and active until the end. She was well organized and was always willing to help and assist students and colleagues at all levels. Her passion for science and music was her driver; she started working at 5 a.m. every day. In conferences, while wearing her characteristic red attire, she was carrying a bag full of papers and proposals to review. She always sat in the first rows and was taking notes; her handwriting was beautiful. She always asked questions to speakers and initiated fruitful discussions.

Her work on carbon started in the 60s, when measuring the magneto-optic response of graphite crystals for establishing the proper identification of electron and holes in the Brillouin zone. She was fascinated by the electronic properties of graphene and in the 80s, she became really interested in the properties of graphite intercalated compounds, and worked together with Gene Dresselhaus and Peter C. Eklund. The field exploded in the 80s and triggered the development of currently used Li-ion batteries that use Li-intercalated graphite. In the late 80s, she got fascinated by the graphite fibers and in particular vapor grown carbon nanofibers produced in Morinobu Endo's Laboratory. At the same time, she was also close to the experiments made by the Exxon research group showing the appearance of

large carbon clusters. She foresaw that these clusters might lead to new science. Indeed, in 1985, similar experiments were carried out by Kroto, Smalley, Curl, Heath and O'Brien at Rice University that led to the discovery of C_{60} and fullerenes. Subsequently, researchers worked on fullerene intercalated alkali metal and discover new superconducting phases. In the early 90s, during an American Physical Society (APS) meeting, Millie and Rick Smalley were asked to provide new directions in fullerene science, and they concurred that if a fullerene could be elongated, the electron transport would be interesting and novel; Millie had in her mind Endo's nanofibers when thinking about this possibility. Soon after, and in collaboration with Riichiro Saito and Mitsutaka Fujita, they predicted the properties of single-walled carbon nanotubes, ranging from metallic to semiconducting depending on chirality (the way the atoms are arranged along the tubule axis). Almost simultaneously, Sumio Iijima published his paper reporting, by electron diffraction, that these concentric tubules have indeed different chiralities. These events led to the explosion of the nanotube field, in which Millie immensely contributed. In the late 90s, Millie pioneered in the area of resonant Raman spectroscopy, in collaboration with Marcos A. Pimenta, Ado Jorio, Antonio G. Souza-Filho. They established this tool as the most effective to identify different carbon allotropes, ranging from fullerenes and nanotubes to graphene, being also able to characterize their quality, and unveil electron-phonon interactions. During the last decade of her life, Millie worked on graphene, graphene nanoribbons, topological insulators, and other 2-Dimensional materials such as chalcogenides and phosphorene.

A few months ago, when I congratulated Millie for the Franklin Medal she was going to receive this 2017, I wrote an email thanking her for her support in my career and she replied to me with a compliment I was not expecting …

Dear Millie,

I just wanted to congratulate you for the Franklin Award!!! You really deserve it and I would also like to thank you for all your support during my academic career. Your guidance and continuous support have been instrumental in the development of my scientific career. Thanks for all and I look forward to seeing you in Japan

Best wishes

Mauricio

———————

Hi Mauricio,

I also thank you for your support.

I am happy to see you taking Peter Eklund's chair at Penn State and taking his vision to the next level.I guess that I see you next somehow in Japan.

Millie

Another anecdote I have with Millie was when she was awarded the Kavli Prize in Nanoscience, during a 2D workshop in Washington, D.C. I was actually the one who passed her on the good news after receiving an email from Gene Dresselhaus, her husband and who could not contact Millie at that time. Gene, sent me an urgent email in the morning of on May 31st, 2012 stating:

Mauricio,

Please get Millie to phone Norway immediately

she has been awarded the Nanoscience prize by the Norwegian Academy of Science. Worth 1 million US dollars"

At that moment, and in the middle of a talk, I crossed the conference room to the front row and showed Millie my cell phone with Gene's email. She said *"Wow, what should I do now?"* I told her *"I think we should go out and call them so you can accept the Kavli prize"*, so we did and I had also the opportunity to be with her during the Kavli ceremony that same year in Oslo. It was unforgettable and a unique celebration, Millie was extremely pleased when receiving this award.

Millie got all possible prizes a scientist could be awarded. Mille received numerous awards and recognitions that include more than 19 honorary degrees, membership of the National Academy of Sciences and Engineering in the US, the Kavli Prize in Nanoscience, The Presidential Medal of Freedom, The Enrico Fermi Award and many others. She is truly a role model, as a mother, scientist and colleague, and we will all miss her, especially we Carbon scientists.

Katsumi Kaneko, Shinshu University

Still I cannot believe that we have missed Millie-san. I would like to express my sincere thanks to Millie-san for encouraging and guiding me (and my colleagues) to creative science.

My good fortune was brought by activated carbon fiber (ACF) which had guided me to Millie-san. Although I was not a carbon scientist, I just started to unveil the structure of ACFs to understand the structure and properties of molecules confined in the micropores of ACF. In 1991, professor Brian McEnaney (University of Bath, a visiting professor of Center for Applied Energy Research (CAER); Kentucky University) and professor Frank Derbyshire (CEAR) invited me to the CAER workshop. I was so nervous to present the invited talk on origin of superhigh surface area of porous carbons. At that time, one of the hot topics of Carbon and Adsorption Science fields is whether the surface area of activated carbon can be larger than the surface area of graphene (2630 m^2/g) or not. Some papers reported that the BET surface area of highly activated carbon was larger than 3000 m^2/g, while other scientists assisted that the surface area larger than 2630 m^2/g originated from the overestimation with the BET method and the surface area of activated carbon must be smaller than 2630 m^2/g.

In my talk, I presented the theoretical reason for the overestimation of the surface area by the BET method and the validity of our new subtracting pore effect (SPE) method for evaluation of the surface area of microporous carbon. Also I showed that the surface area of KOH-activated carbons by the SPE method could be larger than 2630 m^2/g by more than 1000 m^2/g because of the contribution by the edge carbons of the nanoscale graphitic units (Kaneko et al. *Carbon* 1992; 30:1075–1088). After my talk, Millie-san came next to me on the stage, showing a great satisfaction for my presentation with very long comments and then she asked other participants on my presentation points using the blackboard. Thus, my presentation gave rise to a serious delay in the workshop program.

Personally I was so happy to have such an intensive support by Millie-san; I was so encouraged for future research on carbon. I could enjoy our friendship since 1991. Millie-san visited us at Chiba University twice and gave a short Japanese greeting to my children in my home. When she was the committee chair on hydrogen storage (I didn't know the exact committee name), she asked me by telephone through one of my friends Professor Karl Johnson (Pittsburgh) on the possibility of storage of hydrogen by carbon materials; I replied that the high density storage of supercritical hydrogen was impossible by ordinary physical adsorption even using single wall carbon nanotube.

Millie-san educated me indirectly through occasional conversation and collaborative works. I decided to come to Boston this April

to deliver an invited talk at the conference on nanoscience and nanotechnology, but my real aim to attend the conference is to have a time to discuss with Millie-san on a new subject. No more "Hi, Kaneko-san" from Millie-san. Thank you Millie-san for your truly great contribution to outstanding worldwide science.

Peter Thrower, Carbon Editor-in-Chief Emeritus

Although she was only seven years older than I am, I must confess to always having seen Millie as a "grandmother" figure. When I started carbon research and attended my first conferences in the early 1960s she was already well known and respected, and it was a privilege and a pleasure to have been associated with her for the last 55 years. We never collaborated on research and we never visited each other's labs, but we always seemed to be in contact. I suppose our biggest interaction was during the thirty years that I was Editor-in-Chief of *Carbon*. Millie was always willing to review manuscripts, provided one was willing to wait in line! Her reviews were always brief and pointed, and clearly showed her grasp of the subject. I cannot say how many papers she reviewed for me over the 31 years of my tenure, but they were many.

I had the impression that, as far as Millie was concerned, technology could wait and her research came first. In those early years, when manuscripts were submitted on typed sheets of paper, her reviews were often in the form of notes written in the margins and between the lines of text. Fortunately, her writing was neat and clear and it was quite easy for my secretary and I to format them as a review. After most people had adopted Powerpoint®, Millie was still using overheads that were drawn and written freehand, sometimes, she admitted, on her way to the meeting! I clearly remember one meeting at which the organisers had to track down an overhead projector for her use!

For a number of years Millie and I served on the committees of the American Carbon Society. Although Millie was almost always in attendance, it was clear that her research was more important than committee work. She almost always worked on a manuscript while the committee was discussing Society affairs. On one notable exception I remember her reaching into her bag and extracting a pair of socks and some yarn. She then proceeded to darn the socks while the meeting went on. That was the last time I ever saw anybody darning socks!

The one regret I have from my relationship with Millie is that I never heard the Dresselhaus String Quartet. After I learned of her family's musical expertise we often discussed our mutual interest in the subject and what new works we had discovered and had been listening to, but I never heard her play. I understand the ensemble was quite accomplished.

I last saw Millie at the Penn State Conference (2016) and never imagined that this would be the last time I saw her. She was her bright and usual self, and her sudden death came as a great shock. She will be sorely missed.

Morinobu Endo, Shinshu University

I met Prof. Mildred Dresselhaus for the first time at the 2nd international conference on graphite intercalation compounds (GIC's) held at Provincetown, Massachusetts in May 1980. During the conference, I showed carbon fibers obtained by catalytic chemical vapor deposition method with high structural perfection as a host of GICs. She showed large interest in these vapor-grown carbon fibers for contrasting such 1-dimensional carbon (1D) with 3-dimensional (3D) bulk graphite on which she had studied. Our collaboration started in that year and we published together our first joint paper in 1982. As a fledgling researcher, I had been using Prof. Dresselhaus's papers on graphite published during the 1970's as textbooks. For this reason, I had a dream that one day I would coauthor a paper with her on the carbon fiber. She was also very pleased to this paper, and I believe it was because she could expand research interests not only 3D graphite but also other carbon systems with different dimensionality.

During the work on GICs, she developed a scientific interest in GIC's made with 1D carbon and 2D graphene. Her laboratory was well-known for the Raman spectroscopic experiments on all these new types of carbons under strong cooperation with her husband Dr. Gene Dresselhaus. Historically, the concept of "graphene" was newly established by GIC researchers around 1980, in which a single hexagonal carbon network was sandwiched by intercalant layers such as K, Li or Br_2. Indeed, in GICs, single layer or double layers of carbon network are surrounded by intercalant layers as in 1st or 2nd stage GICs.

Based on her large contribution by Raman spectroscopy and wide accumulation of knowledge on carbon materials for such key topics as dimensionality, layered structures, doping or intercalation, and *Raman spectroscopy*, she successfully developed and enlarged the research in the areas followed by high Tc ceramics, thermoelectrics, C_{60}, carbon nanotubes, lithium ion battery, graphene, and related two-dimensional materials. She was always a very challenging and creative person not only in basic science but also in applications, and her contributions were crucial to develop the "nanocarbons" in the era of nanotechnology.

During our collaboration, no matter how late at night, no matter how early in the morning, Prof. Dresselhaus always responded quickly to my inquiries and to those of others. She always conducted herself by the utmost research lifestyle, and I can say her life style as a researcher "Research is her life and her life is research". As a scientist, the basis of Prof. Dresselhaus's attitude toward science was that her most important duty is to contribute to science.

While strict when dealing with research results and discussion, she was always gentle, warm and encouraging for other scientists, especially for young researchers and students. For all these reasons, she was recognized as "Queen of carbon science" and also "common mother" for all researchers of all over the world. And I will never forget her happy smile when she said to me at her house, at Christmas season, that next day we would have a home concert with all the family to come and there she would play violin. May Prof. Mildred Dresselhaus rest in peace.

Hui-Ming Cheng, Institute of Metal Research, Chinese Academy of Sciences

Millie has been one of the most important mentors to me in my research career. She showed me the path into carbon nanotube research, and has provided me with significant support and advice for the 20 years since we first met. In 1997, I came to meet Millie in person for the first time at the Biennial Carbon conference held at Penn State, USA, although I had read and heard so much about her over the years. When she came to see my poster on carbon nanofibres and multi-wall carbon nanotubes by floating catalyst CVD and showed great interest in my work, young and inexperienced as I was, I asked her whether it was possible for me to work with her as a visiting scholar at MIT. She quickly responded "Yes" and even promised to fund me for the visit. I then had the opportunity to work in her lab for about 6 months and published two pioneering papers on the synthesis of single-wall carbon nanotubes produced by floating catalyst CVD, which were the first two papers on carbon nanotubes I ever published and remain quite important until today. Millie was highly efficient and took 'time' very seriously. We always received her feedback and comments on our papers within the next day if she was in her office. At the same time, she was extremely meticulous. No small mistakes were overlooked, and even the misuse of punctuation was corrected.

Undoubtedly she was well known for her extraordinary research and is a true 'Queen of Carbon' in science. What I admire most about her has always been her down-to-earth personality. Millie was so amiable and approachable, especially to young researchers. I believe everyone who has known her would agree that it was an

absolute pleasure to talk to her. More importantly, Millie was so full of wisdom that it slipped out through her words and found ways to reach us without our noticing. I was able to learn and find inspiration from our conversations all the time, although she just appeared to speak casually about her life and work and enjoy some laughs.

She has visited China many times and given lectures in a number of places. She has also visited my lab at IMR twice, where she patiently gave advice and guidance to each of my students. The last time Millie came to IMR was in 2011. She unfortunately had a stomach sickness at that time, but she refused rest at the hotel. Both students and researchers, myself included, were deeply moved as she did not want to waste any time resting but chose to continue the discussions with us.

I am deeply saddened by the news that she has passed away and believe it is a huge loss for the world of science and technology, in particular, carbon science. However, I am also grateful that we have had the honour to share her inspirational life stories and notable career accomplishments, which will certainly inspire us and future generations of researchers.

Michael Strano, Massachusetts Institute of Technology

From my very first encounters with Millie Dresselhaus and her work, she existed larger than life in what is still a fast moving field of nanocarbon science. I was a PhD candidate defending my thesis at the University of Delaware when I started reading her book with Peter Eklund and her husband Gene, “The Science of Fullerenes and Carbon Nanotubes.” I was to start my post doctorial position at Rice University with Richard Smalley, and needed to come up to speed in a rapidly developing subfield of nanotechnology. Millie was my first teacher in this space, making an indelible impression on me as a young scientist as only a giant in a scientific field of giants can make.

It would be two years later towards the end of my post-doctoral work when I would first meet her in person at an American Physical Society meeting. To my good fortune, I found in her a great scientific role model and an extremely generous mentor, interested in both learning from and teaching the young scientists of the field. Millie was indeed a superb mentor of students and showed me, through her actions, the absolute importance of this. She generously extended her mentorship to students in the entire field and not just her own research group, as in my own case. Despite our best intentions, few scientists find the capacity to do this in spite of its obvious importance. Science can be both contentious and collaborative, frustrating and rewarding, but in the end, the central goal is the generation and teaching of knowledge. My post-doctoral work involved the discovery of near infrared fluorescence in semiconducting single walled carbon nanotubes. The resulting excitation profiles of some 40 different species was the first data set with which one could evaluate theoretical optical transitions. This data allowed us to spectrally assign these transitions and directly challenged some earlier attempts at spectral assignments from others, including Millie's research group and collaborators. Millie, in her wisdom and deep intellect, was very much the leader in a dispassionate and scholarly attempt to sort through and resolve the contradictions. She was someone with whom one could have gratifying scientific conversations and come away with new insight.

Last summer, I was both surprised and deeply honored that Millie provided a thoughtful and detailed introduction for me at the International Carbon Conference. The recent nature of this speaks to the suddenness of our loss, and how incredibly active she was right up until the time of her passing earlier this year. My advice and sincere hope for my colleagues in the field is that we resolve to honor her memory by continuing her tradition of generous scientific mentorship of young people, fostering of international collaboration and pursuit of excellence in scientific scholarship.

Robert H. Hurt*, D.D.L. Chung, Mauricio Terrones, Katsumi Kaneko, Peter Thrower, Morinobu Endo, Hui-Ming Cheng, Michael Strano

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Available online 9 May 2017