The Queen of Carbon!*

Mildred Dresselhaus (1930–2017)

Jayeeta Lahiri

Mildred Dresselhaus was one of the most renowned physicists, material scientists, and electrical engineers of our time. She made vital contributions to research on graphite and graphite intercalation compounds, graphene, carbon fibers and nanotubes, fullerenes, and thermoelectric effects of nanostructures. Mildred Dresselhaus was considered the leading expert on carbon materials, and was popularly known in the scientific circles as the "Queen of Carbon". Her immense contributions to the field of carbon materials ushered in the era of carbon nanoscience and technology.

Jayeeta Lahiri, Assistant Professor, School of Physics, University of Hyderabad is interested in studying surface and interface properties of low- dimensional materials like graphene (2D), hexagonal BN (2D), and graphene nanoribbons (1D).

1. Early Years

Mildred Dresselhaus was born as Mildred Spiewak in 1930 in Brooklyn, New York, USA. Her parents were Polish Jewish immigrants who had narrowly escaped the horrors of the Holocaust. Their early years were very difficult due to the Great Depression[1]. Her family moved to a Jewish ghetto in the Bronx when she was 4 years old. Her brother, a musical prodigy, introduced her to the world of music. She started receiving free violin lessons before she turned five and started kindergarten. She continued her music lessons during her elementary and junior high school as a scholarship student at the Greenwich House Music School. Due to her exceptional musical skills, she made many friends from more privileged families outside the neighborhood she lived. Meeting families where parents had a high school and college education inspired her to seek opportunities for better education.

[1] From 1929 to 1945, starting with the United States, many industrialized nations slipped into a severe financial crisis which is widely known as the Great Depression.

Keywords
Carbon nanoscience, graphite, graphene, nanotubes, fullerenes, thermoelectricity, nanostructures.

Mildred was interested in studying science and mathematics. But

*DOI: https://doi.org/10.1007/s12045-019-0778-4

Figure 1. Mildred Dresselhaus (1930–2017). Attributed to ENERGY.GOV [Public domain].

at that time, the high schools offering these subjects were not open to girls. There was only one public high school available for girls in New York City, and it focused on liberal arts. Getting admission to this special school was only possible through a rigorous exam, and only 80 students were accepted from the whole city per semester. After clearing the entrance exam, Mildred got into Hunter High School with guaranteed admission to Hunter College. It was at high school that her friends started calling her 'Millie'.

Mildred was interested in studying science and mathematics. But at that time, the high schools offering these subjects were not open to girls. There was only one public high school available for girls in New York City, and it focused on liberal arts.

During the 1950's, the choice of professions for women was rather limited; one could be a school teacher, nurse, or secretary. Millie joined Hunter College with the intention of becoming a school teacher. Hunter College was known for producing teachers for NY city; its main major was education with a low emphasis on the sciences. Mildred was majoring in liberal arts but still had to take science courses. In the second year of college, she was introduced to modern physics, taught by Rosalyn Yalow, a future Nobel Laureate. Yalow was instrumental in Millie choosing a scientific career over teaching and became her life-long mentor. After graduating from Hunter College in 1951, Millie received a Fulbright Fellowship, which allowed her to attend Cambridge University in England for one year. Her studies during this year focused only on physics. At Cambridge, she was able to cover more topics in physics and make up for the limited number of courses offered at Hunter College. In 1953, she completed her master's degree from Radcliffe College, Cambridge, Massachusetts (now part of Harvard University) [1, 2].

Mildred joined the graduate program in physics at the University of Chicago in 1953. In the first year, she took up the quantum mechanics course taught by Enrico Fermi.

Mildred joined the graduate program in physics at the University of Chicago in 1953. In the first year, she took up the quantum mechanics course taught by Enrico Fermi. Millie came to know Enrico Fermi and his family very well, before his untimely death in 1954. She credits him for making her "think like a physicist". She wanted to work in solid-state physics, and only Andrew Lawson was working in this area, so he became her PhD advisor. Her PhD thesis was titled 'Magnetic field dependence of the surface impedance of superconducting tin'. While at the graduate school, she met her future husband Dr Gene Dresselhaus, a postdoctoral research associate, at the University of Chicago. She defended her PhD thesis and got married in 1958. Soon after, she joined Cornell University for postdoc with the NSF Fellowship where her husband was a faculty. At Cornell, she continued working on the ideas developed during her PhD work.

2. Scientific Career

In 1960, both Mildred and her husband secured jobs at the MIT Lincoln Laboratory because the institute did not have anti-nepotism rules back then, and was willing to hire couples. She started working at the Solid State Division of Lincoln Laboratory (a defense research lab), where she was asked by the then Director to switch her research area from 'superconductivity' to 'anything else'. She subsequently decided to work on the optical properties of graphite (an allotrope of carbon), bismuth and other semimetals. The magneto-optics experiments were considered difficult, and at that time, the graphite electronic structure was consideredto be very complicated. She had very little competition in this field which allowed her to balance her family life and professional career (she had four kids within a span of four years i.e.

1959–1963). This proved to be the best decision for her career.

In 1967, she was invited to a visiting professorship at MIT's Electrical Engineering Department through a grant – the Abby Rockefeller Mauzé Fund for Woman Scholars. In 1968, she was offered a full professorship in the Department of Electrical Engineering and Computer Science. She was the first woman Full Professor at MIT and the first woman Institute Professor (in 1985), the highest honor for MIT professors. These are one of her many 'among the first' feats.

Millie was among the first to use lasers for magneto-optics experiments to investigate the electronic structure of any solid-state system. In collaboration with Ali Javan, inventor of the continuous wave (CW) laser, they designed a series of high-resolution magneto-optics experiments on graphite. Javan made a special laser for these experiments that allowed them to use right and left circularly polarized laser light from a helium-neon laser. In 1968, they proposed a new model for the electronic structure of graphite [3]. Their model was able to explain many of the puzzling results observed and set the stage for more new work on sp^2 hybridized carbon materials. In the 1970s, she started working on graphite intercalated compounds (GICs). Dresselhaus investigated the properties of graphite by inserting molecules between the layers and then probing with time-varying magnetic fields [4, 5]. Her work with graphite and graphite intercalation compounds laid the foundation for lithium-ion batteries (widely used in laptops nowadays). During this time, she extensively collaborated with her husband, Gene Dresselhaus, a theoretical physicist. Together they laid the foundation of 'semimetal physics'.

Dresselhaus investigated the properties of graphite by inserting molecules between the layers and then probing with time-varying magnetic fields. Her work with graphite and graphite intercalation compounds laid the foundation for lithium-ion batteries.

In the early 80s, Dresselhaus was investigating graphite using laser ablation, where a high energy laser beam was used to remove material from a surface. During these experiments, she observed that large carbon clusters[2] were being ejected. At the same time, researchers at Exxon were studying the properties of carbon clusters comprising up to about 15 atoms. After discussing with Professor Dresselhaus about her laser ablation work, they began to look at how carbon atoms are bound together and soon pub-

[2] A cluster is a collection of atoms or molecules. A cluster of 100 Carbon atoms is denoted as C_{100}.

lished a paper showing carbon clusters up to C_{100} [6]. Similar experiments were carried out independently by Richard Smalley and his coworkers at Rice University, which resulted in the discovery of C_{60} – a football-shaped molecule made of 60 carbon atoms – named *Buckminsterfullerene*[3]. The trio of Kroto, Curl, and Smalley was awarded the 1996 Nobel Prize in Chemistry [7].

[3]See Surabhi Potnis, From Carbon to Buckypaper, *Resonance*, Vol.22, No.3 (Women's Special Issue), pp.257–268, March 2017. Also see G K Ananthasuresh, Buckminster Fuller and his Fabulous Designs, *Resonance*, Vol.20, No.2, pp.98–122, February 2017.

In the early 90s, during an American Physical Society (APS) meeting, Millie and Richard Smalley were asked to provide new directions in fullerene science. They proposed that if a fullerene could be elongated to have a tube-like shape, these structures could have novel electron transport properties. These tubular structures, now known as the carbon nanotubes (CNTs), are hollow cylindrical tubes of carbon atoms with the tube diameter in nanometers. Soon after, Millie predicted and then experimentally verified using Raman spectroscopy that single-wall carbon nanotubes (SWNT) could either be semiconducting or metallic, depending on the chiral vector of the nanotube [8–10]. Almost simultaneously, Sumio Iijima, from a competing research group in Japan, published his paper reporting that the concentric tubules in multi-walled CNTs have indeed different chiralities [11]. These discoveries kickstarted a new area of research in carbon materials. She pioneered the use of resonance Raman spectroscopy to investigate CNTs [12].

In the late 90s, she started working on graphene ribbons[4]. She was interested in studying the electronic structure of graphene ribbons and the effect of edges on the electronic band structure. Her work shows that all zigzag nanoribbons are metallic with a high electron density of states near the Fermi level, while the armchair nanoribbons are semiconducting in nature [13]. She also demonstrated that using polarized Raman spectroscopy we can distinguish between the armchair and zigzag edges [14]. Later, she investigated the properties of exotic two-dimensional materials like graphene, molybdenum disulphide, black phosphorus and more [15–17].

[4]If CNTs are cut length wise, we get a long strip of graphene resembling narrow ribbons.

In the 90s, she also started working on thermoelectricity. She wanted to design 'thermoelectric' nanomaterials that could be

Mildred also worked on thermoelectricity and showed that in nanostructures it is possible to decouple thermal and electrical transport with potential for energy conversion.

used to turn waste heat into usable energy. This idea occurred to her during one of the discussions with researchers working in defense labs. She investigated the effects of phonon confinement and electron-phonon interactions in nanostructures. She showed that in nanostructures (1D) it is possible to decouple thermal and electrical transport with potential for energy conversion [18, 19]. Her exceptional work revived the stagnant field of thermoelectricity.

Over a career span of 50 years, she has mentored about 60 PhD students. According to the *Web of Science*, as on 03 May 2017, Millie had published 1,205 papers with a total of 82,983 citations (excluding self-citations), and an h-index of 133. She has co-authored 8 books related to her field of research. She is the recipient of 31 honorary degrees from some of the world's most prestigious institutions including Harvard and Princeton. She was also the Editor of many international journals.

3. A Tireless Advocate of Women in Science

When Millie started out, women were strongly discouraged from pursuing science. She was the only female in a class of 11 PhD students in physics at the University of Chicago. Her PhD advisor at the University of Chicago believed that women had no place in science and completely ignored her. He wasn't even aware of what she was working on until two weeks before she submitted her thesis. During her postdoctoral stint at Cornell, Millie had volunteered to teach a course on electromagnetism to which a senior colleague commented that "a woman could never teach engineering students". At Lincoln Laboratory, she was one of the two female scientists, out of a staff strength of 1000. Here, she was harassed for arriving late or leaving early to take care of her young children. Her female colleague who also faced similar conditions left the laboratory. However, Millie stuck around and proved her credentials, before she was hired as a Professor in MIT's Department of Electrical Engineering and Computer Sciences. Her early experiences as a female scientist made her a strong advocate of women in science.

When she joined MIT, only 4% of undergraduate students and only 1% of faculty members were female. She has worked tirelessly with the MIT administration to improve gender equality in admission processes. By 2017, the number of female undergraduate students had increased to 50%. In 1973, she and a colleague organized the first women's forum at MIT, for exploring the role of women in science and engineering. She also organized the first-year student's forum for boosting the confidence of female students. She would often go out of her way to help and guide the students, especially female students. She had a tremendous impact on the students both inside and outside the classroom. She received a Carnegie Foundation grant to "continue encouraging female students in the traditionally male-dominated field of physics research". She headed the first Committee on the Education and Employment of Women in Science and Engineering organized by the National Research Council in 1975 and later years. In 1997, as a member of Committee on Science, Engineering, and Public Policy – a joint committee of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine – she contributed to the guide *Advice on Mentoring Science and Engineering Students* published by the National Academy Press.

Her early experiences as a female scientist made Millie a strong advocate of women in science. She has worked tirelessly with the MIT administration to improve gender equality in admission processes.

In 1999, Millie received the Dwight Nicholson Medal for Outreach from the American Physical Society "for being a compassionate mentor and lifelong friend to young scientists; for setting high standards as researchers, teachers and citizens; and for promoting international ties in science" [20]. In 2012, she established the Millie Dresselhaus Fund using her Kavli Prize money (one million USD), to help women scientists and junior colleagues at MIT. She believed that "Kavli prize happened because of the investment MIT made in her many years ago through the generosity of others." She established the fund "because this was the best investment she could think of for this money" [21].

Millie was awarded the Dwight Nicholson Medal for Outreach from the American Physical Society "for being a compassionate mentor and lifelong friend to young scientists; for setting high standards as researchers, teachers and citizens; and for promoting international ties in science."

4. Awards and Honors

Millie received numerous awards and honors during her prolific career. The most notable ones include:

- **The Presidential Medal of Freedom (2014)**: She received this award from President Barack Obama. It is the highest accolade bestowed by the US government to American civilians.
- **The Kavli Prize in Nanoscience (2012)**: The Kavli Prize is awarded by the Norwegian Academy of Science and Letters, the Kavli Foundation, and the Norwegian Ministry of Education and Research every two years. She received this award "for her pioneering contributions to the study of phonons, electron-phonon interactions, and thermal transport in nanostructures" [22]. She was the first sole winner of the one million USD Kavli Prize money.
- **Enrico Fermi Award (2010)**: She received this award "for leadership in condensed matter physics, in energy and scientific policy, in service to the scientific community, and in mentoring women in the sciences" [23]. She was the second woman to win this award since the inception of this award in 1954. Enrico Fermi award is a Presidential Award managed by the US Department of Energy.
- **The National Medal of Science (1990)**: She received this award from President George Bush "for her studies of the electronic properties of metals and semimetals, and for her service to the Nation in establishing a prominent place for women in physics and engineering" [24]. She was the first woman to win this medal in engineering sciences since its inception in 1959.

Mildred Dresselhaus also served as the Director of the Office of Science at the US Department of Energy (2000–2001), the President of the American Physical Society (APS) in 1984, the President of the American Association for the Advancement of Science (AAAS) in 1998, the Treasurer of the US National Academy of Sciences, and the Chair of the Governing Board of the American Institute of Physics (AIP). APS established the Millie Dresselhaus Fund for Science and Society to honor her remarkable scientific career and inspiring community legacy [25].

Mildred Dresselhaus was a brilliant researcher, teacher, and mentor. Her success can be attributed to her flexibility in adopting new research directions. Her scientific career is a testament to her passion for science. Her work ethic was unparalleled. For most part of her life, she started working from 5:30 in the morning and continued till late at night. Post-retirement, she started going to the lab late – at 6:30 in the morning. Even at 86, she was actively engaged in research until two weeks before her death on 20th February 2017. She was awarded the Benjamin Franklin Medal posthumously in 2017. She is survived by her husband, four children, and five grandchildren. Millie leaves behind a rich scientific legacy. She is an inspiration to all the women scientists across the world and will continue to inspire the future generations of scientists.

Millie leaves behind a rich scientific legacy. She is an inspiration to all the women scientists across the world and will continue to inspire the future generations of scientists.

Suggested Reading

[1] **L Madsen, *Successful Women Ceramic and Glass Scientists and Engineers: 100 Inspirational Profiles*, Wiley 640, 2016.**

[2] **M Hargittai, *Women Scientists: Reflections, Challenges, and Breaking Boundaries*, New York: Oxford University Press, xiii, 363 pages, 2015.**

[3] **P R Schroeder, M S Dresselhaus, and A Javan, Location of Electron and Hole Carriers in Graphite from Laser Magnetoreflection Data, *Physical Review Letters*, 20(23): pp.1292–1295, 1968.**

[4] **M S Dresselhaus and G Dresselhaus, Intercalation Compounds of Graphite, *Advances in Physics*, 30(2): pp. 139–326, 1981.**

[5] **M S Dresselhaus and G Dresselhaus, New Directions in Intercalation Research, *Molecular Crystals and Liquid Crystals Science and Technology Section A – Molecular Crystals and Liquid Crystals*, 244, pp.1–12, 1994.**

[6] **Eric A Rohlfing, D M Cox and A Kaldor, Production and Characterization of Supersonic Carbon Cluster Beams, *Journal of Chemical Physics*, 81, pp.3322–3332, 1984.**

[7] **H W Kroto *et al.*, C_{60}: Buckminsterfullerene, *Nature*, 318, p.162, 1985.**

[8] **R Saito *et al.*, Electronic-Structure of Graphene Tubules Based on C-60, *Physical Review B*, 46(3), pp.1804–1811, 1992.**

[9] **R Saito *et al.*, Electronic-Structure of Chiral Graphene Tubules, *Applied Physics Letters*, 60(18), pp.2204–2206, 1992.**

[10] **M A Pimenta *et al.*, Raman Modes of Metallic Carbon Nanotubes, *Physical Review B*, 58(24), pp.R16016–R16019, 1998.**

[11] S Iijima and T Ichihashi, Single-shell Carbon Nanotubes of 1-nm diameter, *Nature*, 363, p.603, 1993.
[12] M S Dresselhaus, Fifty Years in Studying Carbon-Based Materials, *Physica Scripta*, T146, 2012.
[13] K Nakada *et al.*, Edge State in Graphene Ribbons: Nanometer Size Effect and Edge Shape Dependence, *Physical Review B*, 54(24), pp.17954–17961, 1996.
[14] R Saito *et al.*, Raman Spectra of Graphene Ribbons, *Journal of Physics-Condensed Matter*, 22(33), 2010.
[15] X Ling *et al.*, The Renaissance of Black Phosphorus, *Proceedings of the National Academy of Sciences of the United States of America*, 112(15), pp.4523–4530, 2015.
[16] X Ling *et al.*, Raman Enhancement Effect on Two-Dimensional Layered Materials: Graphene, h-BN and MoS_2, *Nano Letters*, 14(6), pp.3033–3040, 2014.
[17] M Kalbac *et al.*, Large Variations of the Raman Signal in the Spectra of Twisted Bilayer Graphene on a BN Substrate, *Journal of Physical Chemistry Letters*, 3(6), pp.796–799, 2012.
[18] L D Hicks and M S Dresselhaus, Effect of Quantum-Well Structures on the Thermoelectric Figure of Merit, *Physical Review B*, 47(19), pp.12727–12731, 1993.
[19] M S Dresselhaus *et al.*, New Directions for Low-dimensional Thermoelectric Materials, *Advanced Materials*, 19(8), pp.1043–1053, 2007.
[20] American Physical Society, https://www.aps.org/.
[21] http://news.mit.edu/2013/mildred-s-dresselhaus-fund
[22] The Kavli Prize, [cited 2018; Available from: http://kavliprize.org/prizes-and-laureates/laureates/mildred-s-dresselhaus.
[23] US Department of Energy, Office of Science, [cited 2018; Available from: https://science.energy.gov/fermi/award-laureates/2010s/dresselhaus/.
[24] National Science and Technology Medals Foundation, https://www.nationalmedals.org/laureates/mildred-s-dresselhaus.
[25] American Physical Society, Millie Dresselhaus Fund for Science & Society.

Address for Correspondence
Jayeeta Lahiri
School of Physics
University of Hyderabad
CUC, Professor CR Rao Rd
P O, Central University
Gachibowli, Hyderabad
Telangana 500 046, India.
Email:
jayeeta.lahiri@gmail.com