Plasma Generation by Household Microwave Oven for Surface Modification and Other Emerging Applications

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Abstract

A simple and inexpensive method to generate plasma using a kitchen microwave is described in this paper. The microwave-generated plasma is characterized by spectroscopic analysis and compared with the absorption spectra of a gas discharge tube. A Paschen-like curve is observed leading to a hypothesis of the microwave plasma generation mechanism in air. We have also demonstrated that this microwave-generated air plasma can be used in a multitude of applications such as: a) surface modification of a substrate to change its wettability; b) surface modification to change electrical/optical properties of a substrate; and c) enhancement of adhesive forces for improved bonding of polymeric microfluidic molds, such as bonding polydimethylsiloxane (PDMS) chips to glass covers. These simple techniques of plasma generation and subsequent surface treatment and modification applications may bring new opportunities leading to new innovations not only in advanced labs, but also in undergraduate and even high school research labs.
I. INTRODUCTION

Plasma is ubiquitous in nature and readily observed as lightning on a stormy night, or as a static electric spark the moment before touching a door knob on a dry winter day\textsuperscript{1}. It is also found naturally occurring in stars\textsuperscript{2}, solar winds\textsuperscript{3}, upper atmospheric lighting\textsuperscript{4} and the awe generating lightning glow known as St. Elmo’s fire\textsuperscript{5} that sailors wondered about for centuries. Practical applications of plasma span a vast domain including, but not limited to, fusion energy generation\textsuperscript{6–9}, plasma TV displays\textsuperscript{10}, plasma enhanced chemical vapor deposition (PECVD)\textsuperscript{11}, sputtering\textsuperscript{12}, semiconductor device fabrication\textsuperscript{13,14}, substrate cleaning\textsuperscript{15} and sterilization\textsuperscript{16}. Plasma is also referred to as the fourth state of matter\textsuperscript{17}. As the addition of energy to material in a solid or first state initiates a phase change to a liquid second state and then to a gaseous third state, adding a sufficient amount of energy to a gas may ionize the gas by ejecting electrons from the outer shells and/or through collisions of individual ions. Plasma, the fourth state\textsuperscript{17}, is thus composed of a conducting soup of energised charged particles, electrons and ionized atoms/molecules that are normally generated by the application of strong electromagnetic or heat energy. Once this highly charged gas is brought in contact with a surface, some energy is transferred from the plasma to the substrate surface, in turn changing the surface property of the substrate. Unfortunately, plasma instrumentation remains somewhat sophisticated and expensive, preventing its widespread use in teaching and research environments for institutions with small budgets. In the past some attempts were made to bring plasma research and analysis to high school and undergraduate teaching and research labs\textsuperscript{18–20}, however, they either involve gas discharge tubes that require high voltage and vacuum levels, or high temperature flames\textsuperscript{21} for the proposed experiments, raising potential safety concerns and related issues in elementary labs. Beck et. al.\textsuperscript{22} also computed trajectories of electrons in a weakly coupled plasma obtained from particle simulations. However, the goal of nearly all of these earlier theoretical or experimental papers for undergraduate students was to characterize plasma and experimental/numerical verification of the theory of plasmas. In a recent paper\textsuperscript{23} popular science activity of forming plasma in a microwave with grapes showed that grapes act as spheres of water, which, due to their large index of refraction and small absorptivity, form leaky resonators at 2.4 GHz. When brought together, Mie resonances in isolated spheres coherently add up so that the aqueous dimer displays an intense hotspot at the point of contact. When this hotspot is
sufficient to field-ionize available sodium and potassium ions, it ignite a plasma.

In contrary to the previous works, here we show that a simple plasma treatment apparatus can be constructed from an inexpensive household microwave oven and a modified vacuum flask and showed many modern application of this microwave-generated plasma. Although some previous works have shown that plasma can be sparked when a gas held at low pressure is subjected to microwave radiation\(^{24-35}\), this technique has never received the attention it deserves when it comes to low cost laboratory technique for wide range of surface treatments. We demonstrate a number of cutting-edge applications of the plasma device that we have constructed which includes the modification opto-electrical properties of semiconductors, changing wettability of substrates, enhancement of bonding between certain polymers such as PDMS and glass and reduction of graphene oxide to graphene for electronics purposes etc.

Before going into the details of the microwave generated plasma generation process, we believe a comprehensive discussion about past works on microwave breakdown of air, similarities and differences between previously observed breakdown phenomena and our plasma generation observation is necessary to put our work in proper perspective. In general plasma generation process under DC conditions is relatively well understood where avalanche multiplication of electrons in a neutral gas are produced through electron impact ionization (or photoionization) when electrons or photons with sufficient energy collide with neutral atoms and molecules present in the medium\(^{36}\). However, under the influence of an oscillating electric field instead of a DC field the ions and electrons would oscillate back and forth in between the electrodes and for a very high frequency only a very small number of charged particles would be able to reach the boundary electrodes reducing the diffusive loss of electron energy.

The first serious investigation of microwave breakdown in air was conducted by Herlin and Brown\(^{32}\). Theoretical basis of their analysis consists of solving the continuity equation for the electron number density in their custom made cavity geometry, accounting for the source of electrons as impact ionization and loss terms by diffusion and attachment corresponding to the gas in use. Their custom made microwave source was a continuous wave tunable magnetron that operated at about 3 GHz. In order to isolate the microscopic phenomena leading to breakdown they used specifically designed cavities (i.e., cavities that resonated at the \(TM_{010}\) mode) so that gas pressure and electric field strength were at all times well-
known. A radioactive source was placed near the discharge that provided a small amount of ionization in the cavity to start with, and the microwave field in the cavity was increased until the cavity suddenly began to glow (at which time the microwave field abruptly decreased). The radioactive source in their case was the supplier of the triggering electrons. They found that the breakdown field was smaller at about 3 Torr than it was at higher or lower pressures under these conditions. This minimum also appeared to be a weak function of cavity size. According to the results they have also found that the dominant mechanism for breakdown of a low pressure gas at microwave frequencies is ionization by collision of electrons with neutral gas molecules rather than loss by diffusion to the walls of the discharge tube.

Afterwards considerable research was done using fundamentally the same apparatus. Gould and Roberts\textsuperscript{33} also used a cavity resonated at the $\text{TM}_{010}$ mode and a 85 millicurie cobalt 60 radioactive source of was placed on the cavity in order to ensure the presence of sufficient number of electrons in the discharge region even before the microwave was turned on. They also concluded that under these conditions the mechanisms controlling breakdown in air were electron generation by impact ionization, and loss by attachment and diffusion. Good agreement between the theory and their experiment over a wide range of parameters verified the assumptions and the values of the coefficients used in the theory. Of note is the extension of the theory to include as a loss mechanism for electrons the attachment of electrons to neutral molecules, thus creating negatively-charged molecules (of note also is that recombination, the coalescence of an electron with an ion to form an atom, is negligible).

MacDonald, Gaskell, and Gitterman\textsuperscript{34} extended the range of frequencies studied, and investigated air, nitrogen, and oxygen independently. With the exception of some X-band cavities, all of their cavities were also cylindrical and resonant in the $\text{TM}_{010}$ mode. They also reported the necessity of having a 5 millicurie cobalt 60 gamma-ray source next to the cavities to produce sufficient ionization to get repeatable results for pulsed waves and 5 microcurie source for continuous wave process. Their measurements agreed with previous measurements. They critiqued the previous theory by noting it assumed an electron-molecule collision frequency that was independent of electron energy, when it had long been known that the electron-nitrogen collision frequency was in fact strongly dependent on electron energy. While unable to present an improved analytic theory, they were able to present an alternative representation that allowed an empirical method of calculating breakdown fields.
in a very large variety of conditions.

MacDonald, Gaskell, and Gittermans work was extended to form the final chapter (and appendix) of MacDonalds book\textsuperscript{30}. As had been the case in Herlin and Browns work, in order to achieve reproducible results a radioactive source (5 millicourie Co$^{60}$) was placed again near the cavity in this work. Bandel and MacDonald\textsuperscript{35} further measured breakdown electric fields in air, H$_2$O, and air plus H$_2$O at 3.06 GHz. In their case triggering electrons for the discharge were supplied not by a radioactive source, but by photo-electric emission by ultraviolet light, introduced into the cavity from a synchronized spark discharge in room air. Care was taken to attenuate the uv as needed to avoid lowering of the breakdown threshold. They found that even in the presence of triggering electrons from photo-electric emissions the breakdown field strengths for mixture of air plus 17.2 Torr of water vapor were up to about 25\% greater than for dry air at the same total pressure, thus quantifying the effect of water vapor molecules in microwave plasma generation in their resonant cavity geometry.

In case of breakdown fields required when using very short microwave pulses MacDonald\textsuperscript{30} also confirmed that in the absence of an electron from some auxiliary source, the breakdown field measured would be very large, since the initial electrons would have to be provided by field emission or other surface effects.

In the context of all these previous serious works on microwave breakdown of air\textsuperscript{30–35}, we would like to point out that there are four distinct differences between the previous studies and our present work: a) minimum pressure required for plasma initiation in our chambers is orders of magnitude less than that of the previous ones, i.e, in the order of $\sim 10^{-2}$ Torr in our experiments in comparison to the order of $\sim 1$ Torr in the previous studies, b) minimum electric field required in our studies is $\sim 10^1$ V/cm, which is the standard average electric field present in a kitchen microwave, in comparison to $\sim 10^2$ V/cm or higher in the previous studies mentioned. Moreover, we used fixed power, fixed frequency microwave oven and we didn’t vary average electric field as done previously, c) our plasma chamber is not specifically designed as a resonating cavity for any specific mode as done previously, rather, two different arbitrary shaped glass flasks and two different microwave ovens of different sizes produced similar qualitative results; and lastly, d) no external source of triggering electrons either in the form of radioactive sources or synchronized photo-electric emissions were necessary to generate plasma in a microwave oven as seen in the video\textsuperscript{37} even in much lower electric field environment.
II. PLASMA GENERATION BY A KITCHEN MICROWAVE

A. Materials and methods

FIG. 1. A schematic of the construction of the sample holder for the microwave-generated plasma is shown in this figure. One of the crucial parts needed is a simple air-tight valve. An inexpensive one can be fabricated from specialty parts as shown here, by modifying a PTFE and glass burette tip and rubber stopper. Bottom left to right: the sample is inserted into the Erlenmeyer flask; the vacuum valve is opened and the vacuum pump is used to evacuate the flask; the valve is closed and the vacuum hose removed; the flask is transferred to the microwave oven, and as the microwave is turned on, plasma is sparked to treat the surface for the desired length of time. To characterize the spectrum of the plasma, this process is repeated without a sample while placing a UV-Vis spectrometer in front of the microwave window.

The main component of this low-cost plasma etching system is a regular kitchen microwave oven and a vacuum flask/sample holder. Any robust, vacuum-gauge glass container will work, but we have found the Erlenmeyer flask is the simplest and least expensive. The
flat bottom of this glassware gives extra stability during sample preparation which may be useful in a teaching environment. A valve must be attached to the flask stopper which can be opened while evacuating the chamber and closed again to seal and hold the vacuum. Speciality microwave-resistant valve parts can be purchased, but here we have sought a frugal alternative first. The ideal substitute for this part was determined to be the detachable two-part tips found on many burettes (Fig.1). These parts consist of an all PTFE housing and stopcock into which a glass tip is loosely inserted. The glass tip of the burette can be easily removed by twisting it slightly. Next, a rubber stopper with a hole in the center, such as those for inserting thermometers into reaction vessels, is used. This part is selected to fit the mouth of the Erlenmeyer flask used above. The glass burette tip above is then inserted through the bottom of the stopper until it protrudes from the top by about 10mm. The PTFE stopcock housing is then placed back over the protruding burette tip. All of the edges of this system are then sealed with regular silicone glue. The seal is sufficient to hold a vacuum for many hours. We have also found that a properly matched valve connector stopcock stopper for vacuum desiccators can serve this purpose also (Fig.2). The main point here is that the design of the container is not limited to the ones described here, rather using any microwavable vacuum container with a stopcock valve should produce plasma. A vacuum hose can be directly attached to the top of the valve allowing the system to be evacuated to various pressures with a small vacuum pump. Once the properly evacuated flask is put in the microwave and the oven is turned on, after a few seconds glowing plasma

FIG. 2. An alternative microwavable vacuum container to generate microwave plasma.
forms inside the flask (please watch the video of plasma generation⁴⁷). The time difference between the first observation of plasma and the time of turning on the microwave oven, i.e., the plasma initiation time, is recorded for different vacuum pressures. Furthermore, by flushing the evacuated system with various gases like argon, nitrogen, oxygen etc., this system can be used to determine the effect of different plasma chemistries. A schematic of the whole process is shown in Fig.1. In all of the following experiments, the substrate or sample is placed in an Erlenmeyer flask, the vacuum hose is attached, and the pressure is lowered with a vacuum pump to the desired value. The valve is then sealed and the flask transferred to the microwave oven. Once the microwave oven is turned on after a short delay, the plasma sparks, and then the plasma is allowed to glow for the desired amount of time.

B. Characterization of the microwave-generated plasma

![Graph showing plasma initiation time as a function of vacuum pressure](image)

**FIG. 3.** Plasma initiation time measured and plotted as a function of vacuum pressure in two different flasks. A Paschen-like curve is observed when the pressure of the flasks are reduced and placed in the microwave oven to record plasma initiation time. At ambient pressures and high vacuum, the initiation time grows asymptotically, while in the intermediate regime, plasma sparks consistently within a few seconds. If the pressure in the flasks becomes too low, higher initiation time is observed pointing towards low number density of molecules in the flasks and corresponding lower collision cross section. Data for two flasks, one 125 ml and the other 250 ml show similar asymptotic behavior.
The plasma generated by this method is analyzed using two simple but revealing techniques: a) recording plasma initiation time as a function of the vacuum pressure, which is also a measure of particle density at constant temperature, and b) measurement of UV-visible emission spectra of the plasma glow. A Paschen-like graph\textsuperscript{38,39} is generated by plotting the plasma initiation time with the vacuum pressure of the flask to varying level (Fig. 3). A trough-shaped curve resulted from this analysis, showing asymptotic tendencies at high and low vacuum pressures and a sweet-spot regime in between in which the plasma sparks within a matter of seconds. To generate a classical Paschen curve in a gas discharged tube the breakdown voltage (or energy required for plasma initiation) between two electrodes is normally recorded as a function of pressure. However, in our system, energy required for plasma generation is supplied through constant power kitchen microwave, and the time the flask is exposed to microwave radiation determines the amount of energy supplied to the system. So, in our case we have plotted the microwave exposure time to initiate plasma as a function of the pressure of the flasks.

Although Herlin\textsuperscript{32} or MacDonald’s\textsuperscript{30} theory based on the dynamics of impact ionization and diffusion loss were able to produce good match between their theory and experiments done in their chosen custom made resonant cavity geometry in presence of triggering electrons, our experimental results in a very different experimental conditions as described in the introduction section raises many unexplained questions that require fresh and in depth investigation. One such important question is about the origin of primary electrons in our set up in absence of any radio active source or photoemitters, since without a source of triggering electrons in a low electric field environment it is nearly impossible to start the electron avalanche process. Although actual source of triggering electrons is still unknown and further studies are needed, we hypothesize that the presence of stray water vapor molecules along with microwave field distortion near some edges, or cosmic ray dependent ionization may have some effect on the generation of primary electrons in a flask under microwave radiation. We believe that this is a plausible hypothesis since Bandel and MacDonald\textsuperscript{35} also reported that even in the presence of a radio active source as a supplier of sufficient triggering electrons, presence of water vapor may affect the plasma generation process significantly ($\sim 25\%$). Water is a polar molecule\textsuperscript{40,41} with dipole moment $\mu$ ( $|\mu| \sim 6.2 \times 10^{-30}$ C.m) and it is well known that an instantaneous electric field can generate a torque to align these polar molecules in the direction of the instantaneous field (Supplementary Fig. 16,17). In the
FIG. 4. The figure shows a possible mechanism of kitchen microwave generated plasma formation. Firstly, it is well known that electromagnetic waves in a standard kitchen microwave form a standing waves with a wavelength of 12 cm in a 2450 MHz. The electrical field component of the imposed electromagnetic wave excites the polar molecules like water. Positive charge centers of the polar molecules would experience a force/torque in the direction of the electric field while the negative charge centers would experience that in the opposite direction. Sufficiently strong and high frequency electrical field component of the applied microwave would be able to spin/vibrate the water molecules very fast and may eventually tear the negative and positive charge centers apart, most likely while hitting an atom/molecule/cosmic ray, and creating primary electrons and positive ions in the flask. Secondly (a-d), these primary electrons would accelerate opposite to the instantaneous applied electric field and collide with other molecules present in the flask on their way forward. If the electrons gather enough momentum before the collisions they will be able to knock out secondary electrons from the molecules/atoms they hit; in turn ionizing them also. These secondary electrons would then start to accelerate and may generate more and more electrons along the way creating a chain reaction. This is the pathway of the Townsend-type avalanche we normally observe in a gas discharge plasma. A comparison of the plasma generated in a gas discharge tube and that in a microwave shows similar absorption spectra and supports this mechanism of microwave plasma generation.

oscillating electric field of a microwave water molecules are thus supposed to wobble/spin in synchronization with the field, in turn creating highly energized oscillating/rotating water
molecules as shown in Fig.4. An order of magnitude calculation of the torque $\vec{\tau} = \vec{p} \times \vec{E}$ produced by a household microwave with frequency $f = 2.45 \text{ GHz}$ and amplitude of electric field $|\vec{E}| \sim 2 \times 10^3 \text{ V/m}$, shows that the microwave electric field may generate an enormous angular acceleration $\alpha$ of a water molecule ($|\vec{\alpha}| = \vec{\tau}/I \sim 10^{20} \text{ rad/s}^2$, $I \sim 3 \times 10^{-47} \text{ Kg.m}^2$ being the moment of inertia of water molecule about the specific rotation axis. In actual scenario, however, the dynamics of asymmetric top type rotating water molecules are much more complex and may give rise to additional rotational instabilities, such as classical spin flipping, as observed in our zero gravity parabolic flight experiment done with a toy water molecule. Moreover, it is also reported that intermolecular bonds get stretched in rapidly rotating molecules and there can be additional effects of electron screening to weaken the bond. The effect of time varying magnetic fields on the diamagnetic water molecules, presence of cosmic rays, other sources of emissions etc. may also bring additional complexity to the dynamics. Whether these highly energized water molecules colliding with other atoms/molecules or other sources are capable of producing primary electrons is subject to debate. We think that it is still an open question and we invite other researchers to explore these unanswered questions.

Once the primary electrons are generated, it is plausible to assume that they will accelerate in the opposite direction of the instantaneous electric field and collide with any atom/molecule that come in their way creating secondary electrons and ions. Based on their charges these electrons and ions accelerate either towards, or in the opposite direction of the electrical field. A simple calculation shows that in response to the electric field the rate of kinetic energy gain in electrons is much higher than that of the corresponding ions. In case an electron of mass $m_e$ and charge $|q_e|$ is generated by collision along with a massive ion of mass $M_i$ and charge $|q_e|$ and both of them accelerate in an average electric field $E$, the ratio of kinetic energies of an electron and the ion can be obtained as $K.E_e/K.E_{ion} = M_i/m_e$. As $M_i/m_e >> 1$, it is clear that electrons would be much more energetic in comparison to the massive ions in ionizing the gas in the flask and starting the cascading chain reaction leading to plasma. It is also well known that the ion-molecule collision frequency is about $\sqrt{m/M} \ll 1$, so one can expect that the rate of ionization due to electron-molecule collision will be orders of magnitude higher than the rate of ionization due to ion-molecule collisions. It is well known that in electron-molecule collision frequency varies linearly with both the speed of the electrons and the electron-molecule collision cross section. So,
we hypothesize that speed of the electrons and electron-molecule collision cross section are two important parameters in the plasma generation process in a kitchen microwave. Since pressure in the plasma chamber at ambient temperature is directly proportional to the number density of the constituent particles, one can control the mean free path by lowering the number of constituent gas molecules or by lowering the pressure. At ambient pressure the number of constituent gas molecules in the flask is quite large and hence mean free path is too short (as mean free path is inversely proportional to the gas density). So, at higher pressure it would be difficult for the electrons to accelerate for a long distance and gain enough momentum (and kinetic energy) in between two successive collisions and cause an impact ionization chain reaction. Therefore plasma won’t spark in this regime. As the pressure is decreased though, number density of particles decrease and the mean free path becomes sufficiently large for the knocked out electrons to gain enough momentum (and kinetic energy) to cause the nearby atoms to ionize upon collision, depending on their ionization energies. This is a possible mechanism that creates a sky-blue plasma which is visible in the first 1-2 seconds after ignition (please see the supplementary figures for illustrations). Further complexity in the collision mechanism can happen due to the collision of electrons and vigorously rotating water vapor molecules also. However, the chain reaction continues and molecules with higher ionization energy becoming ionized next due to collisions with electrons previously created. This regime is characterized by a deep purple and then pink plasma ball. When the vacuum pressure is decreased further to 68 mTorr or less for a 250 ml flask and 69 mTorr or less for a 125 ml flask, the collision cross section of electrons with molecules becomes too small for plasma to spark, and hence the plasma ignition time tends towards infinity in this asymptotic limit. Thus, we believe that two competing mechanisms are at interplay here: a) kinetic energy of the electrons accelerating in an electric field to knock out further electrons from atoms/molecules and b) collision cross section of the electrons and gas molecules in the flask. These two dominant regimes are visible in two asymptotic limits in Fig.3 as explained above. In the sweet spot the collision cross section and the kinetic energy of the electrons are just right to initiate plasma. We have two different kitchen microwaves and the same overall characteristic remains the same, although the plasma initiation times may vary slightly depending on the size and geometry of the microwave ovens.

UV-Visible absorption spectra of plasma are also recorded using a desktop CCD spectrometer (Exempler, B&WTek) and is shown in Fig.5. The spectra of the microwave
The microwave-generated plasma spectra is compared with the corona discharge (gas discharge) tube air plasma spectra. Nitrogen and oxygen lines are visibly identified in both the spectra. Plasma clearly show the dominant nitrogen and oxygen peaks indicating ionization of these molecules. To test our hypothesis of the microwave plasma generation we also built a gas discharge tube with fixed electrodes, generated air plasma in it and compared the spectra obtained from the gas discharge tube with that generated by the microwave. The reason behind this comparison is that gas discharge plasma is very well studied and the plasma generation mechanism of a gas under a constant strong electric field leading to Townsend avalanche is well known. The striking similarity of both the spectra (Fig. 5) lead us to confirm that although the source to energise gas is different in two cases: a) electric field in a gas discharge tube, while b) electromagnetic radiation in microwave-generated plasma, the chain reaction is somewhat similar as described in Fig. 4.

III. APPLICATIONS OF MICROWAVE PLASMA

Plasma treatment is a well-known technique to remove any contaminant, change surface energy, modify electrical and thermodynamic properties of a substrate for various purposes. A change in the surface energy of a substrate can easily be ascertained by measuring the contact angle of a liquid on the surface. The contact angle of a liquid drop, i.e., the angle measured where a three-component interface exists between a liquid drop, a solid surface, and
the ambient air is measured by first taking cross sectional pictures of the drop using a camera and then analysing the contour of the drop using a software. Normally the designation of a hydrophobic material is reserved for surfaces with a liquid contact angle of greater than 90°. Contact angles of less than 90° indicate a hydrophilic material with good wetting properties.

A. PDMS surface modification by plasma treatment

A flat PDMS substrate is prepared by mixing the PDMS liquid elastomer and the curing agent (Sylgard 184) in 10:1 ratio followed by degassing and incubating for a couple of hours resulting in a consistent, bubble-free soft solid block. Soft cured PDMS blocks are then cut to shape and placed in the vacuum flask. The flask is evacuated to (500 mTorr) and placed in the microwave for plasma treatment. Once the plasma sparks, the PDMS blocks are treated for 2, 3, 4, and 5 seconds respectively. The relative change in surface energy is evaluated by measuring the contact angle of a water micro-droplet placed first on an untreated and then on the treated surfaces using a micropipette. We have used the open source image processing software ImageJ with DropSnake plugin to measure the contact angle of the sessile micro-droplet. Fig.6 clearly shows that the contact angle of water on the microwave-plasma treated PDMS sample increases nearly linearly with the treatment time indicating a direct relationship between the change in surface energy and microwave-plasma etching. Surprisingly this observation is exactly opposite to the effect observed in regular gas discharge plasma treated PDMS surface where in absence of microwave just oxygen plasma lowers the contact angle and makes the substrates more wetting. To further investigate this opposite effect of microwave plasma and to understand what role the microwave plays in this reversal of contact angle we have investigated the effect of microwave on a PDMS substrate with and without plasma Fig.6. It shows that while microwave (without plasma) has some small effect on making the PDMS surface less wetting as the contact angle rises from 63° to 70° with 10 s treatment time, the effect of microwave plasma is much larger as the contact angle changes from 63° to 159° with just 5 s of plasma treatment. We propose that the adsorbed water molecules on the surface of the PDMS substrate plays a crucial role here. One plausible explanation is that the surface adsorbed thin film of water gets heated up by the microwave component and simultaneously a rapid interaction with high density ions through
the plasma contacts embeds ions on the soft-baked PDMS substrate surface leading the substrate towards superhydrophobicity. This microwave-plasma treatment technique is thus useful for making hydrophobic surfaces for water-resistant coatings and other applications, that can’t be achieved through gas discharge plasma treatment, as well as for bonding PDMS to glass substrates and other applications, as investigated in detail in a later section.

**Surface modification of ZnO thin films to change its opto-electrical property.**

Plasma treatment of a metal oxide thin film can also change its opto-electrical property. A film of ZnO particles was prepared as previously described\(^5\). Briefly, a suspension of ZnO particles were deposited on a glass microscope slide from a 60% (v/v) solution of ethanol. The film was air dried for several minutes and then annealed on a hot plate by ramping the temperature from ambient to 500 °C in 7 minutes. Previous work has shown that as the ZnO film cooled a layer of ambient moisture and gases, as well as ethanol which is trapped in the bulk microstructure of the ZnO, deposits onto the ZnO surface\(^5\). This is verified by a strong OH band centered at 3400 cm\(^{-1}\) in the FTIR spectrum of the film. The sample and substrate were transferred to the vacuum flask. The flask was then evacuated and the whole assembly was placed in the microwave oven as before. The plasma was sparked and allowed to interact with the ZnO surface for 4, 8, and 15 seconds. FTIR analysis of the treated surfaces in Fig.7 show a decrease in the overall intensity especially of the OH band (centered at 3400 cm\(^{-1}\)). Our previous work\(^5\) has shown that such modification of polycrystal and nanocrystal semiconducting films plays an important role in the electronic properties of the material.

**Reduction of graphene oxide to graphene**

Graphene is a 2D wonder material\(^5\) with many potential applications ranging from flexible electronics, energy storage, sensors to molecular sieving\(^5\). One hurdle in further developing graphene applications commercially however is the difficulty in preparation of bulk graphene in mass scale. One way of producing graphene is chemical vapor deposition (CVD), which is expensive and requires expensive instrumentation. Graphene is most easily produced in bulk by the reduction of graphite oxide solutions, but this can be time-consuming
FIG. 6. Change in contact angle of water in a microwave oven, with and without plasma. Droplet pictures at the top show that increasing contact angle with extended plasma treatment time by adding sufficient surface energy of the soft cured PDMS polymer substrate. To differentiate the effects of microwave and microwave plus plasma one can choose a suitable pressure (say 2000 mTorr) and put the substrate in a 250 ml flask. As this pressure is above the higher asymptotic limit of the Paschen-like curve (Fig.3) turning the microwave on won’t spark plasma in the chamber. However, if we put an identical sample in a 125 ml flask at the same 2000 mTorr pressure and turn the microwave on, the substrate can be treated with both microwave and plasma, thus giving us a way to differentiate the effects of microwave plasma quantitatively.

and is not an environmentally friendly process. Some recent works have shown alternative optical and thermal processes for obtaining reduced graphene oxide using laser\textsuperscript{61,62}. Here we show that plasma generated by our simple system is capable of providing the local energy
FIG. 7. The figure shows the result of plasma etching a ZnO nanowire thin film. The film was fabricated as for all devices (deposition from ethanol suspension) followed by sintering. The etching was conducted for 4, 8 and 15 seconds. The inset showing the band at 3400 cm\(^{-1}\) due to the -OH bond in alcohols. The intensity of this signal clearly diminishes as the film is etched indicating a loss of electron-withdrawing groups from the surface of the material. The large signal at around 2100 cm\(^{-1}\) is from CO\(_2\) and the band at around 900 cm\(^{-1}\) is due to a small amount of glass particles that were scraped off of the device substrate. The graphs shown above are the FTIR analysis of ZnO nanowire thin films, however other ZnO thin films made of ZnO particles or nanoparticles also show similar behaviour under plasma etching.

needed to reduce dielectric graphene oxide films to conductive graphene (Fig. Raman).

First, graphene oxide (Graphenea Inc.) is drop casted onto polyethylene terephthalate (PET) film. After drying for 24 hours at 50 °C, the GO-coated foil is cut into squares. The sheet resistance of each square is measured using a Keithley Source Meter with a four-point Kelvin probe. The resistance prior to plasma etching show a large value on the order of 10 MΩcm\(^{-2}\).

One graphene oxide square is taped on either end to a glass substrate and then placed in the plasma etching flask. It is then evacuated for 1 minute (to a pressure of 300 mTorr). The flask is placed in the microwave for 4 seconds. The other two squares are also treated for 4 seconds, but neither affixed to substrates and one treated for 4 and 1 second intervals
FIG. 8. Raman spectra and absorption studies for graphene oxide (GO) and plasma treated graphene oxide (PTGO) films.

FIG. 9. Graphene oxide films before (L) and after (R) treatment in 4 seconds of air plasma. Clearly the free-standing sample is not very useful for applications despite is large change in resistance. A similar change in resistance was attained by treating the bursts-sample with four separate 1-second pulses of plasma, which prevented the plastic substrate from warping significantly.

instead of continuous exposure. The third is exposed to plasma for 4 seconds continuously. The three types are referred to as supported, bursts, and free-standing, respectively as shown in Fig.9.

The resistance following plasma etching is measured and showed a reduction of resistance of about two orders of magnitude. The lowest final resistance is obtained for the free-standing sample, but the heat from the plasma caused the plastic foil to warp, making this
process less useful for flexible electronic applications.

B. Bonding of Microfluidic Channels to Substrates

Many materials like polypropylene (PP), polyether ether ketone (PEEK), PDMS or poly-oxymethylene (POM) are extremely hard to bond with other materials. Requirement of high bonding strength, durable and irreversible bonding of metal, glass and plastics present special challenges for the manufacturing industry. Plasma treatment of a surface with other applied cleaning procedures produce better adhesion capability and bonding strength on the surfaces to be joined in comparison to untreated substrates.

Microfluidics is an emerging technology with fluid flow in micrometer or less size channels and has tremendous applicability\textsuperscript{63}. Applications for microfluidics include mobile chemical analysis\textsuperscript{64}, medical diagnostics\textsuperscript{65}, drug delivery\textsuperscript{66}, soft robotics\textsuperscript{67}, RNA encapsulation\textsuperscript{68}, and nanomaterials synthesis\textsuperscript{69} to name a few. In order to fabricate robust microfluidic devices, it is necessary to have a strong bond between the microfluidic polymer mold (typically PDMS) and the substrate. A strong bond prevents the device from leaking, becoming damaged, or the development of passages by which the confined solutions could escape the network of channels. Plasma has been used in this application extensively, as it converts the exposed surface of the PDMS into dangling silane groups, allowing a very strong bond to glass to be formed. We demonstrate that the plasma generated in our simple microwave system can be used for this purpose.

The following steps are taken to create PDMS microfluidic channels bonded on glass: (1) A microchannel mold is created (typically using photolithography or other methods). (2) A mixture of liquid PDMS and cross-linking agent is then mixed in the 10:1 ratio and poured into the mold in a petri dish. The petri dish is kept in an incubator at 65 °C for a couple of hours. (3) The hardened PDMS is taken off the mold. A replica of the microchannels is obtained on the PDMS block. (4) To complete the microfluidic chip and to allow the

| Substrate   | Initial resistance $R_i$ (MΩcm$^{-2}$) | Final resistance $R_f$ (MΩcm$^{-2}$) | $\Delta R$ (%) |
|-------------|----------------------------------------|--------------------------------------|----------------|
| Supported   | 5.4                                    | 0.2                                  | 96.3           |
| Free-standing | 10.5                                   | 0.1                                  | 99.0           |
| Bursts     | 7.9                                    | 0.1                                  | 98.7           |
FIG. 10. A schematic to bond PDMS mold to glass to make microchannels.

FIG. 11. Adhesive force of the untreated PDMS surface is measured using AFM force spectroscopy method.

injection of fluids for future experiments, the inlets and outlets of the microfluidic device are punched with a biopsy puncher whose diameter is slightly less than the size of the tubes to be connected. This will ensure tight fitting of the inlet/outlet tubes to the channels. (5) Finally, the side of the PDMS with open microchannels and the glass slide are treated with plasma to obtain closed channels with one flat inner wall of glass and all other walls of PDMS. (6) The plasma treatment irreversibly bonds PDMS with glass and makes the
microfluidic chip.

FIG. 12. Adhesive force of the PDMS surface is measured using AFM force spectroscopy method before and after various degrees of plasma treatment.

A freshly made PDMS replica and a glass microscope slide in two different vacuum flasks were used in this experiment. The flasks were evacuated to 500 mTorr (0.5 Torr) and three seconds of plasma exposure was used on both of them. After plasma treatment, the glass slide was removed and placed on a flat surface. The PDMS sample was then removed and the treated surface is placed in the desired location on the glass slide; the two components were then pressed together gently and allowed to sit for ten minutes. A schematic of the whole process is shown in Fig. 10.

We have also measured the adhesive force of a PDMS surface before and after treatment using force-distance microscopy mode of an atomic force microscope (Nanosurf C3000 Flex-AFM) and the representative graph is shown in Fig. 11. The relative change in adhesive force due to surface plasma treatment is shown in Fig. 12.

IV. CONCLUSION

In this work we have demonstrated that a simple plasma etching device can be constructed from a household microwave oven and a vacuum flask. We have showed that this apparatus can be used in surface treatment of a substrate for several cutting-edge research applications. Varying degree of plasma exposure to a PDMS substrate leads to change in surface energy and hence a change in contact angle of a water droplet on the substrate was observed before and after the surface treatment. Upon exposure to plasma a change in opto-electrical properties of a metal oxide semiconductor such as ZnO was demonstrated.
using FTIR spectra analysis. Significant change in electrical resistance of graphene oxide thin films was also observed as an effect of plasma exposure. Moreover, it was also shown that irreversible bonding between certain elastomers like PDMS and glass can be achieved to make microfluidic channels with this simple technique. Needless to say that the domain of these applications is enormous and our hope is that this paper, through this frugal alternative to conventional and expensive plasma treatment, would enable more researchers to delve into these cutting edge research areas leading to more innovation and discovery.

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VI. REFERENCES

1 Curt Supplee and Kristi Donahue. *The plasma universe*. Cambridge University Press Cambridge, 2009.

2 SV Lebedev, JP Chittenden, FN Beg, SN Bland, A Ciardi, D Ampleford, S Hughes, MG Haines, A Frank, EG Blackman, et al. Laboratory astrophysics and collimated stellar outflows: The production of radiatively cooled hypersonic plasma jets. *The Astrophysical Journal*, 564(1):113, 2002.

3 Marcia Neugebauer and Conway W Snyder. Solar plasma experiment. *Science*, 138(3545):1095–1097, 1962.

4 David D Sentman and Eugene M Wescott. Observations of upper atmospheric optical flashes recorded from an aircraft. *Geophysical Research Letters*, 20(24):2857–2860, 1993.

5 Stanley Singer. The unsolved problem of ball lightning. *Nature*, 198(4882):745, 1963.

6 Gianfranco Federici, Charles H Skinner, Jeffrey N Brooks, Joseph Paul Coad, Christian Grisolia, Anthony A Haasz, Ahmed Hassanein, Volker Philipps, C Spencer Pitcher, Joachim Roth, et al. Plasma-material interactions in current tokamaks and their implications for next step fusion reactors. *Nuclear Fusion*, 41(12):1967, 2001.

7 DG Whyte, AE Hubbard, JW Hughes, B Lipschultz, JE Rice, ES Marmar, M Greenwald, ICzegler, A Dominguez, T Golfinopoulos, et al. I-mode: an h-mode energy confinement regime with l-mode particle transport in alcator c-mod. *Nuclear Fusion*, 50(10):105005, 2010.

8 AE Hubbard, DG Whyte, RM Churchill, ICzegler, ADominguez, TGolfinopoulos, JW Hughes, JE Rice, IBespamyatnov, MJ Greenwald, et al. Edge energy transport barrier and turbulence in the i-mode regime on alcator c-mod. *Physics of Plasmas*, 18(5):056115, 2011.

9 Robert J Goldston. Energy confinement scaling in tokamaks: some implications of recent experiments with ohmic and strong auxiliary heating. *Plasma Physics and Controlled Fusion*, 26(1A):87, 1984.

10 JP Boeuf. Plasma display panels: physics, recent developments and key issues. *Journal of Physics D: Applied Physics*, 36(6):R53, 2003.
11 M Chhowalla, KBK Teo, C Ducati, NL Rupesinghe, GAJ Amaratunga, AC Ferrari, D Roy, J Robertson, and WI Milne. Growth process conditions of vertically aligned carbon nanotubes using plasma enhanced chemical vapor deposition. *Journal of Applied Physics*, 90(10):5308–5317, 2001.

12 Shuyan Xu, Jidong Long, Lina Sim, Cheong Hoong Diong, and Kostya Ken Ostrikov. Rf plasma sputtering deposition of hydroxyapatite bioceramics: synthesis, performance, and biocompatibility. *Plasma processes and polymers*, 2(5):373–390, 2005.

13 W Nicholas G Hitchon. *Plasma processes for semiconductor fabrication*, volume 8. Cambridge University Press, 2005.

14 Noah Hershkowitz. Role of plasma-aided manufacturing in semiconductor fabrication. *IEEE Transactions on Plasma Science*, 26(6):1610–1620, 1998.

15 W Petasch, B Kegel, H Schmid, K Lendenmann, and HU Keller. Low-pressure plasma cleaning: a process for precision cleaning applications. *Surface and Coatings Technology*, 97(1-3):176–181, 1997.

16 Michel Moisan, Jean Barbeau, Marie-Charlotte Crevier, Jacques Pelletier, Nicolas Philip, and Bachir Saoudi. Plasma sterilization. methods and mechanisms. *Pure and Applied Chemistry*, 74(3):349–358, 2002.

17 D Frank-Kamenetskii. *Plasma: the fourth state of matter*. Springer Science & Business Media, 2012.

18 Stephanie A Wissel, Andrew Zwicker, Jerry Ross, and Sophia Gershman. The use of dc glow discharges as undergraduate educational tools. *American Journal of Physics*, 81(9):663–669, 2013.

19 I Alexeff, JT Pytlinski, and NL Oleson. New elementary experiments in plasma physics. *American Journal of Physics*, 45(9):860–866, 1977.

20 W Gekelman, P Pribyl, J Wise, A Lee, R Hwang, C Eghtebas, J Shin, and B Baker. Using plasma experiments to illustrate a complex index of refraction. *American Journal of Physics*, 79(9):894–902, 2011.

21 CS Maclatchy. A low-cost experiment in plasma physics for the advanced undergraduate lab. *American Journal of Physics*, 45(10):910–913, 1977.

22 Arnaud Beck and Nicole Meyer-Vernet. The trajectory of an electron in a plasma. *American Journal of Physics*, 76(10):934–936, 2008.
23 Hamza K Khattak, Pablo Bianucci, and Aaron D Slepkov. Linking plasma formation in grapes to microwave resonances of aqueous dimers. *Proceedings of the National Academy of Sciences*, 116(10):4000–4005, 2019.

24 Mutsukazu Kamo, Yoichiro Sato, Seiichiro Matsumoto, and Nobuo Setaka. Diamond synthesis from gas phase in microwave plasma. *Journal of Crystal Growth*, 62(3):642–644, 1983.

25 Chris Bower, Otto Zhou, Wei Zhu, DJ Werder, and Sungho Jin. Nucleation and growth of carbon nanotubes by microwave plasma chemical vapor deposition. *Applied Physics Letters*, 77(17):2767–2769, 2000.

26 Yihong Wu, Peiwen Qiao, Towchong Chong, and Zexiang Shen. Carbon nanowalls grown by microwave plasma enhanced chemical vapor deposition. *Advanced Materials*, 14(1):64–67, 2002.

27 Shinichi Tachi, Kazunori Tsujimoto, and Sadayuki Okudaira. Low-temperature reactive ion etching and microwave plasma etching of silicon. *Applied Physics Letters*, 52(8):616–618, 1988.

28 Katey Lo, Joseph Summers, Vladimir Bulovic, and Rajeev Ram. Nanomaker. Massachusetts Institute of Technology: MIT opencourseware. https://ocw.mit.edu, 6.S079, Spring 2013.

29 Victor J Law and Denis P Dowling. Converting a microwave oven into a plasma reactor: A review. *International Journal of Chemical Engineering*, 2018, 2018.

30 Alexander D McDonald. *Microwave breakdown in gases*. Wiley, 1966.

31 VA Lisovskii. Criterion for microwave breakdown of gases. *Technical Physics*, 44(11):1282–1285, 1999.

32 Melvin A Herlin and Sanborn C Brown. Breakdown of a gas at microwave frequencies. *Physical Review*, 74(3):291, 1948.

33 Lawrence Gould and Louis W Roberts. Breakdown of air at microwave frequencies. *Journal of Applied Physics*, 27(10):1162–1170, 1956.

34 AD MacDonald, DU Gaskell, and HN Gitterman. Microwave breakdown in air, oxygen, and nitrogen. *Physical review*, 130(5):1841, 1963.

35 HW Bandel and AD MacDonald. Microwave breakdown in air plus h2o. *Journal of Applied Physics*, 41(7):2903–2905, 1970.

36 H Conrads and M Schmidt. Plasma generation and plasma sources. *Plasma Sources Science and Technology*, 9(4):441, 2000.

37 Benjamin Bares Das Kausik S. Video on generating plasma in a microwave. https://youtu.be/oigKfyzEpiU.
38 John Townsend. *The theory of ionization of gases by collision*. Constable, Limited, 1910.

39 Ekram Husain and RS Nema. Analysis of paschen curves for air, n2 and sf6 using the townsend breakdown equation. *IEEE Transactions on Electrical Insulation*, (4):350–353, 1982.

40 Alistair Steyn-Ross and Alister Riddell. Standing waves in a microwave oven. *The Physics Teacher*, 28(7):474–476, 1990.

41 JK Gregory, DC Clary, K Liu, MG Brown, and RJ Saykally. The water dipole moment in water clusters. *Science*, 275(5301):814–817, 1997.

42 Heather Hosack, Nathan Marler, and Dan MacIsaac. Microwave mischief and madness. *The Physics Teacher*, 40(5):264–266, 2002.

43 David Eisenberg, Walter Kauzmann, and Walter Kauzmann. *The structure and properties of water*. Oxford University Press on Demand, 2005.

44 Bane Nathan Ogunnossayi Ayobami Omidokun Jesudara Persad Aaron Das Kausik S, Derickson Justin. Video on the instability of rotating toy water molecules in zero gravity. *https://youtu.be/TXShPMEhjdY*.

45 HJ Bakker, S Wouterson, and H-K Nienhuys. Reorientational motion and hydrogen-bond stretching dynamics in liquid water. *Chemical Physics*, 258(2-3):233–245, 2000.

46 Ran Cai, Hongwei Yang, Jinsong He, and Wanpeng Zhu. The effects of magnetic fields on water molecular hydrogen bonds. *Journal of Molecular Structure*, 938(1-3):15–19, 2009.

47 Joel Rasch. *Microwave Gas and Multipactor Breakdown in Inhomogeneous Fields*. Chalmers University of Technology, 2012.

48 F Massines, N Gherardi, N Naude, and P Segur. Glow and townsend dielectric barrier discharge in various atmosphere. *Plasma Physics and Controlled Fusion*, 47(12B):B577, 2005.

49 Norihiro Inagaki. *Plasma surface modification and plasma polymerization*. CRC Press, 2014.

50 Guillaume Lamour, Ahmed Hamraoui, Andrii Buvailo, Yangjun Xing, Sean Keuleyan, Vivek Prakash, Ali Eftekhar-Bafrooei, and Eric Borguet. Contact angle measurements using a simplified experimental setup. *Journal of Chemical Education*, 87(12):1403–1407, 2010.

51 Say Hwa Tan, Nam-Trung Nguyen, Yong Chin Chua, and Tae Goo Kang. Oxygen plasma treatment for reducing hydrophobicity of a sealed polydimethylsiloxane microchannel. *Biomicrofluidics*, 4(3):032204, 2010.

52 Benjamin Kerr Barnes and Kausik S Das. Resistance switching and memristive hysteresis in visible-light-activated adsorbed zno thin films. *Scientific Reports*, 8(1):2184, 2018.
53 Thanh Thuy Trinh, Ngoc Han Tu, Huy Hoang Le, Kyung Yul Ryu, Khac Binh Le, Krishnakumar Pillai, and Junsin Yi. Improving the ethanol sensing of zno nano-particle thin filmsthe correlation between the grain size and the sensing mechanism. *Sensors and Actuators B: Chemical*, 152(1):73–81, 2011.

54 Kostya S Novoselov, Andre K Geim, SVb Morozov, Da Jiang, Mic Katsnelson, IVa Grigorieva, SVb Dubonos, Firsov, and AA. Two-dimensional gas of massless dirac fermions in graphene. *Nature*, 438(7065):197, 2005.

55 Andre K Geim and Konstantin S Novoselov. The rise of graphene. *Nature Materials*, 6(3):183, 2007.

56 Xiaowei Yang, Chi Cheng, Yufei Wang, Ling Qiu, and Dan Li. Liquid-mediated dense integration of graphene materials for compact capacitive energy storage. *Science*, 341(6145):534–537, 2013.

57 AH Castro Neto, Francisco Guinea, Nuno MR Peres, Kostya S Novoselov, and Andre K Geim. The electronic properties of graphene. *Reviews of Modern Physics*, 81(1):109, 2009.

58 Evelyn N Wang and Rohit Karnik. Water desalination: Graphene cleans up water. *Nature Nanotechnology*, 7(9):552, 2012.

59 Chi Cheng, Gengping Jiang, Christopher J Garvey, Yuanyuan Wang, George P Simon, Jefferson Z Liu, and Dan Li. Ion transport in complex layered graphene-based membranes with tuneable interlayer spacing. *Science Advances*, 2(2):e1501272, 2016.

60 Chi Cheng, Gengping Jiang, George Philip Simon, Jefferson Zhe Liu, and Dan Li. Low-voltage electrostatic modulation of ion diffusion through layered graphene-based nanoporous membranes. *Nature Nanotechnology*, 2018.

61 Maher F El-Kady, Veronica Strong, Sergey Dubin, and Richard B Kaner. Laser scribing of high-performance and flexible graphene-based electrochemical capacitors. *Science*, 335(6074):1326–1330, 2012.

62 Maher F El-Kady and Richard B Kaner. Scalable fabrication of high-power graphene micro-supercapacitors for flexible and on-chip energy storage. *Nature Communications*, 4:ncomms2446, 2013.

63 Nam-Trung Nguyen, Steven T Wereley, and Steven T Wereley. *Fundamentals and applications of microfluidics*. Artech House, 2002.

64 Hongfeng Yin, Kevin Killeen, Reid Brennen, Dan Sobek, Mark Werlich, and Tom van de Goor. Microfluidic chip for peptide analysis with an integrated hplc column, sample enrichment col-
umn, and nanoelectrospray tip. *Analytical Chemistry, 77*(2):527–533, 2005.

65 R Edwin Oosterbroek and Albert Berg. *Lab-on-a-chip: miniaturized systems for (bio) chemical analysis and synthesis*. Elsevier, 2003.

66 Petra S Dittrich and Andreas Manz. Lab-on-a-chip: microfluidics in drug discovery. *Nature Reviews Drug Discovery, 5*(3):210, 2006.

67 Michael Wehner, Ryan L Truby, Daniel J Fitzgerald, Bobak Mosadegh, George M Whitesides, Jennifer A Lewis, and Robert J Wood. An integrated design and fabrication strategy for entirely soft, autonomous robots. *Nature, 536*(7617):451, 2016.

68 Delai Chen, Kevin T Love, Yi Chen, Ahmed A Eltoukhy, Christian Kastrup, Gaurav Sahay, Alvin Jeon, Yizhou Dong, Kathryn A Whitehead, and Daniel G Anderson. Rapid discovery of potent siRNA-containing lipid nanoparticles enabled by controlled microfluidic formulation. *Journal of the American Chemical Society, 134*(16):6948–6951, 2012.

69 Yujun Song, Josef Hormes, and Challa SSR Kumar. Microfluidic synthesis of nanomaterials. *Small, 4*(6):698–711, 2008.

70 How to turn a kitchen microwave into a plasma-etching device. MIT Technology Review, Aug 2, 2018.

71 Mitchell Monica Baldwin Charles G Das Kausik S, Gonick Larry and Kairo Moses. Holistic development of undergraduate students concept cartoons to authentic discovery. *Journal of Systemics, Cybernetics and Informatics, 17*(4):13–17, 2019.
SUPPLEMENTARY MATERIALS

We are also using the plasma generation using a kitchen microwave experiment as a classroom demonstration in an effort to engage students in the discussion on some of the important concepts in electromagnetism in undergraduate physics. We have created a pool of multiple choice concept cartoon questions to initiate discussions during classroom lectures on important concepts such as the nature of electromagnetic radiation, relationship between force/kinetic energy of a charge and the applied electrical field, dipole moment vector and the torque applied by an oscillating electric field, collision cross section and cascading effect to generate plasma etc. Impact of similar cartoon questions were measured and reported\(^1\). High resolution pictures of these slides, i.e., Fig.13-Fig.30, can be obtained from the corresponding author of this paper.

**FIG. 13.** This slide elaborates that we are surrounded by the electromagnetic waves.
FIG. 14. This slide can be used to elaborate the concept of dipole moment vector.

FIG. 15. Dipole moment of water molecules.
4. In a uniform electric field $\mathbf{E}$, a dipole will rotate. If the dipole's charges are $\pm q$ and its length is $r$, what torque does the field generate on the dipole?

A. $qEr \sin \theta$
B. $qEr \cos \theta$
C. $qEr \tan \theta$
D. $qEr \cot \theta$

**FIG. 16.** This slide leads to the discussion of torque applied by an electrical field on a dipole.

5. A bunch of tiny dipoles are flying around in random directions and orientations. What happens when a uniform electric field is turned on?

A. Nothing.
B. Torque on the dipoles aligns them along the field lines.
C. The dipoles begin moving along the field lines.
D. The dipoles begin to zig-zag.

**FIG. 17.** Allignment of a group of dipoles along the direction of a steady electrical field.
6. What happens to a dipole in an oscillating electric field?

A. Nothing.
B. It aligns perpendicular to the field lines.
C. It slides back and forth along the field lines.
D. It spins or wobbles in sync with the field oscillation.

FIG. 18. This slide elaborates oscillation of a dipole in an oscillating electric field.

7. A cup of water’s temperature goes up in a microwave oven. Why?

A. There is hidden fire in microwaves.
B. An oscillating electric field spins/wobbles water molecule dipoles, which agitate each other by intermolecular forces.
C. Microwave particles move water molecules by bouncing off them.
D. Microwaves heat the air inside the oven, which warms the water by convection.

FIG. 19. This slide illustrates that in a kitchen microwave oven water molecules oscillate in an oscillating electric field. However, due to hydrogen bonding between the molecules and viscosity of water the oscillating molecules rapidly dissipate energy, in turn heating up the substrate.
FIG. 20. One possible explanation to generate primary electrons. However, as discussed in Section II.B, more work is needed to confirm this scenario.

FIG. 21. Effect of instantaneous electric field on positive and negatively charged particles.
FIG. 22. This slide can be used to initiate discussions on the effect of mass of the charged particles under the influence of an electric field on their kinetic energies after equal time interval.

10. Suppose an electron flies off a (much more massive) spinning molecule. In an electric field, both particles accelerate. At \( t \) seconds’ time after the breakaway, which particle has greater kinetic energy?

A. The electron.
B. The ion.
C. They have equal kinetic energies.

FIG. 23. This is a follow up question on the effect of mass of the charged particles under the influence of an electric field on their kinetic energies.

11. You’re a gas molecule in the chamber of a microwave oven. Electrons are flying off of neutral molecules. Which kind of particle can do you more damage, electrons or ionized molecules?

A. Electrons, because they have higher kinetic energy.
B. Ions, because they are more massive.
C. Both are equally likely to do damage.
D. Why worry? How dangerous is a tiny particle, anyway?
FIG. 24. This slide demonstrates the mechanism of secondary electron generation and ionization of an atom/molecule by the primary electron.

A. It becomes negative.  B. It becomes positive.  C. It remains neutral.

FIG. 25. This slide demonstrates the chain reaction and the path towards plasma generation by Townsend type avalanche effect.
14. The liberated electrons' mean free path is the average distance they fly before colliding with something. If gas pressure is reduced by pumping gas out of the flask (at constant temperature), what happens to the electrons' mean free path?

A. The mean free path decreases (electrons don't fly as far) because molecules expand to fill the space.
B. The mean free path increases (electrons fly farther) because there is more space between molecules.
C. Mean free path does not change because the electric field in the microwave oven is oscillating.

FIG. 26. This slide demonstrates the effect of gas pressure on the mean free path.

15. If electrons' mean free path increases in an electric field, what happens to the electrons' average kinetic energy?

A. The kinetic energy of electrons does not change in an electric field.
B. Average kinetic energy goes down because the particles decelerate over time.
C. Average kinetic energy goes up because the particles have more time to accelerate before colliding with something.
D. There is not enough information to draw a conclusion.

FIG. 27. This slide demonstrates that longer mean free path means more time for the electrons to gain more kinetic energy before the next collision.
16. When gas density is very high, and electrons’ mean free path is very short, how is plasma formation affected?

A. A plasma will form more rapidly because electrons will quickly collide with molecules.
B. A plasma will form more slowly (or not at all) because electrons will not pick up enough energy to ionize molecules.
C. Gas density has no effect on plasma formation.

FIG. 28. This slide demonstrates that shorter mean free path means less kinetic energy for the electrons before the next collision.

17. Bianca is watching a lot of electrons flying in the same direction away from her. The collision cross section of the gas is (roughly speaking) the amount of Bianca’s field of view that is taken up by molecules. What happens to collision cross section as gas density changes?

higher density lower density

A. Collision cross section does not depend on gas density.
B. Collision cross section goes down with increased density.
C. Collision cross section goes up with increased density.

(Imagine that pale blue electrons are flying into the screen.)

FIG. 29. This slide demonstrates that effect of pressure on the collision cross section of electrons with other constituent gas molecules.
FIG. 30. This slide initiates a discussion on how decreasing gas pressure may decrease collision cross section and in turn reduce the probability of generating higher order electrons in turn adversely affecting the possibility of plasma generation.
FIG. 31. This slide initiates a discussion on the asymptotic nature of plasma initiation with respect to the pressure of the gas. We have seen that at constant temperature, very low gas pressure reduces collision cross section, while high gas pressure reduces electrons' average kinetic energy. Thus there should be a sweet spot between these two competing parameters where the condition for plasma generation is just right.