the Bell Jar

Vacuum Technique and Related Topics for the Educator & Amateur Investigator

Notes from the Vacuum Shack

No. 4 March 2020

Late February and March have been very busy months for me thus stalling a few projects. After this, the immediate plan is to get the BVES documentation on the web site, hopefully by early April.

This issue will contain a couple of recycled articles from the print edition of *the Bell Jar* along with some notes on high voltage power supplies using readily available parts.

How Fast do Little Particles Fall in Vacuum?

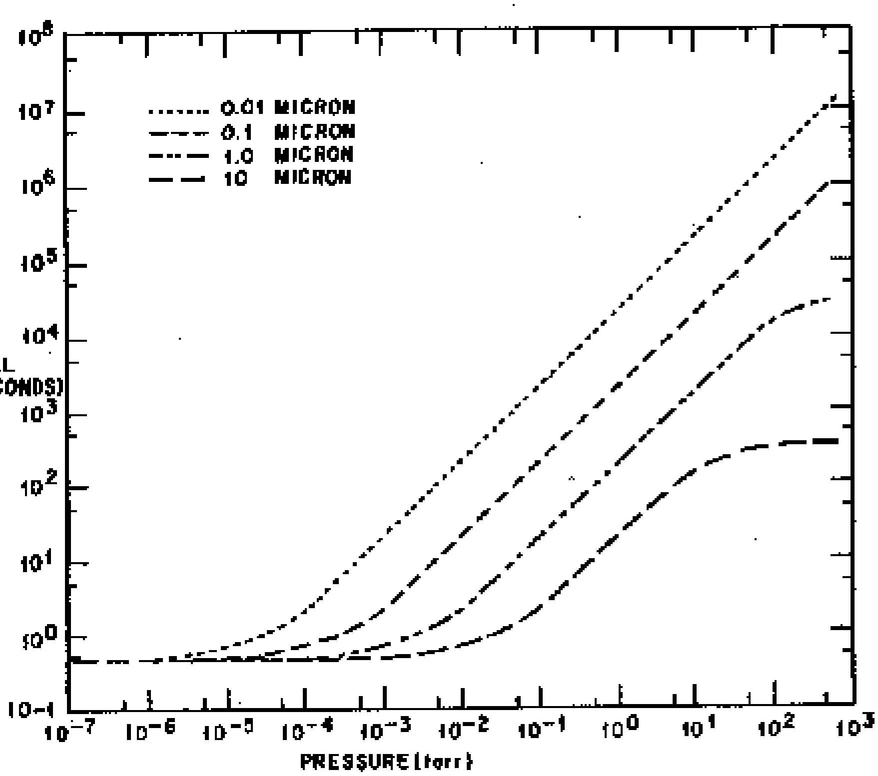
This article originally appeared in Volume 9, Number 3/4.

Almost everyone is familiar with the “penny and feather” vacuum demonstration. In this classic classroom exercise a penny and feather are held at the top of a long clear glass or plastic tube. With atmospheric pressure inside the tube the penny and feather are released together and the penny, being denser and thus less affected by air drag, will fall at a much faster speed than that of the feather. The next step in the demo is to repeat the drop test with the gas in the tube substantially exhausted with a vacuum pump. Without the drag of air, both articles fall at essentially the same speed.

This demonstration not only teaches something about drag but it also clearly refutes the commonly held belief that gravity somehow doesn’t exist in a vacuum environment (a belief resulting, no doubt, from the early days of the space program where Walter Cronkite was always talking about the weightless vacuum environment of space).

The motion of small particles in vacuum has become important in terms of contamination control in semiconductor vacuum process equipment. A way of controlling the migration of small particles is by moving and processing the wafers in a low pressure environment. Thus the vacuum not only makes the processing environment cleaner, it also inhibits the drifting of the small particles that always exist in some number, even in a modern cleanroom. How much the particles will drift or float determines how much of this stuff will waft onto the surface of the wafers. That the particles stay put is important.

The figure on the next page shows the time required for particles of different sizes to fall one meter under varying degrees of vacuum, starting at atmospheric pressure. Note that at pressures of 10^{-5} Torr or less even 100 Å particles will fall one meter per second, and larger particles will fall faster. (Large particles will simply fall ballistically, at the acceleration of gravity.) Thus, an atmosphere with a pressure below 10^{-5} Torr means that particles 100 Å or larger are not likely to be transported onto the critical wafer surface by random air currents or Brownian drift



Fall Time *vs*. Pressure for Small Particles. Cecil J. Davis, *et al*., 1993. Public domain.

Some Resources and Ideas for Plasma Experiments

This article originally appeared in Vol. 4 No. 2. Some minor updates are included.

During late 1994 and into 1995 I received a considerable amount of material from Prof. Robert Jones of the Department of Physics at Emporia State University in Emporia, KS. Prof. Jones' interests lie primarily with experimental plasma physics and he has constructed an interesting array of simple bench top apparatus for plasma studies.

Plasma Experiments with Commercial Gas Tubes

Prof. Jones brought to my attention a number of articles that have appeared in the *American Journal of Physics*, a publication of the American Association of Physics Teachers. Each of these articles deals with experiments that may be performed with commercial gas tubes such as the OA4-G (argon-filled cold cathode triode), 884/885 (argon-filled thermionic triode), and 886 (mercury-vapor rectifier). It is still possible to procure these tubes (or equivalents) from outlets such as vintage radio equipment suppliers and eBay.

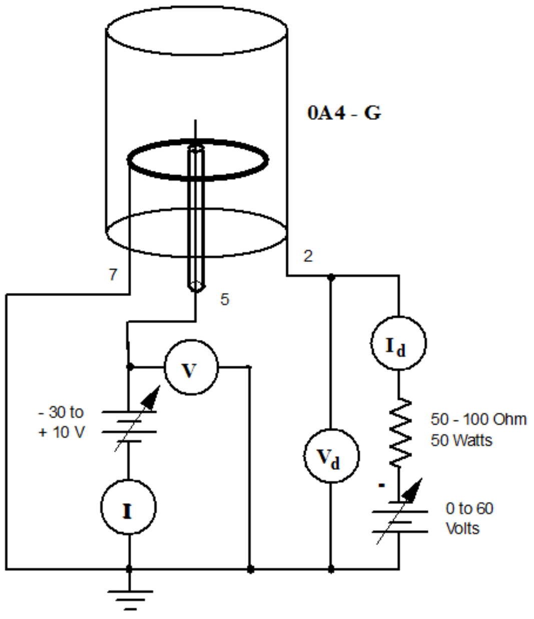
The use of commercial tubes permits a considerable amount of experimentation without the need for vacuum apparatus. However, the techniques, once understood, are completely applicable to “real” applications.

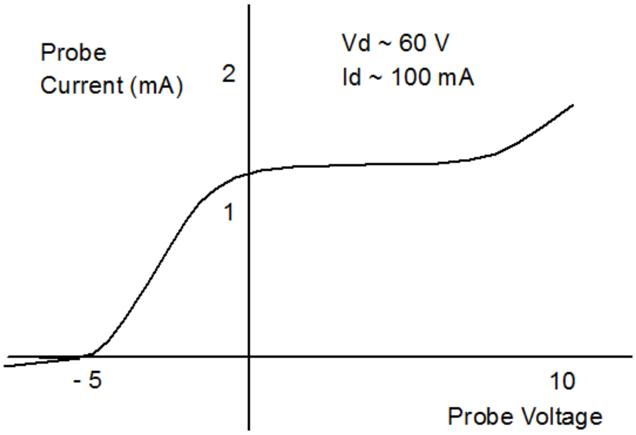
In this note I won’t go into the details of the experiments but will only outline the experiments that are described. Detailed explanations of the concepts may be found in almost any text on plasma physics.

The first article is *New Elementary Experiments in Plasma Physics* (I. Alexeff, J.T. Pytlinski and N.L. Oleson, September 1977). Four experiments are described:

1. Plasma Familiarization - Measurement of *e*/*m* (charge to mass ratio of the electron) and the ionization potential of argon using the 884.
2. Plasma Diagnostic Experiment – Measurement of plasma electron temperature and electron density by a single Langmuir probe using the OA4-G.
3. Observation of the plasma electron frequency using the 866-A.
4. Investigation of the decaying plasma using the 866-A.

The second experiment, as adapted by Jones, is diagrammed in the figure below. I note this experiment because of the importance of the Langmuir probe in plasma diagnostics.





A Langmuir probe is nothing more than a wire that is inserted into a plasma to measure its potential. Early experimenters let the probe float and measured the voltage with a high impedance meter. That gave totally erroneous measurements because the floating probe would permit charges to accumulate. Langmuir’s technique involved connecting the probe to a source of variable potential. The probe voltage is swept and the resulting current *vs*. voltage characteristic, will yield the electron and ion currents to the probe.

The figure shows how the OA4-G is connected for this experiment. A discharge is triggered between the cylindrical cathode at pin 2 and a ring shaped anode at pin 7. The electrode at pin 5 serves as the probe. This electrode is surrounded by a glass sleeve to a point at the plane of the ring anode. The unsheathed portion extends about 6 mm beyond the sleeve.

In the experiment, a discharge is struck between the anode and cathode. This may require about 200 volts. Once the discharge is started the voltage must be reduced to about 60 volts to avoid damaging the tube. After a period of warm-up, the probe is swept by incrementally varying the variable supply. A curve of the type shown in the figure will be developed.

As many plasma devices utilize magnetic confinement fields, a couple of the articles describe experiments in which the OA4-G is immersed in a field. Now, all OA4-A tubes are not created equally. The above described tube with its long iron-alloy cathode is not appropriate for experiments with magnetic fields as the cathode quite effectively shields the discharge. However, there is a variation with a very short cathode in which the anode and probe structures are above the cathode, exposed. As the tube number is the same, you will have to do a bit of digging to find the right tube.

Experiments in a solenoidal field are described in *Behavior of a Single Langmuir Probe in a Magnetic Field* (J.T. Pytlinski, H.J. Donnert and I. Alexeff, December 1978).

Experiments in more complex magnetic fields are detailed in *Characteristics of a Langmuir Probe in a Magnetic Field* (Jonathan Katz, Edward F. Gabl, Eugene K. Tsikis and Karl E. Lonngren, August 1984). Here, multi-dipole magnetic fields as might be encountered in plasma apparatus such as fusion reactors and ion sources are simulated by surrounding the tube with up to 16 small disk magnets that are attached to the inside of a steel coffee can, 3 lb. size.

Some more complex experiments using the OA4-G are contained in *Some Plasma Physics Experiments on Electrical Conductivity and Similarity Laws* (J.T. Pytlinski and I. Alexeff, December 1977). Let's just say that if you have the courage to try some of the above experiments, you'll probably like these too.

The experiments detailed in the first noted article are easy to set up and conduct and any amateur seriously interested in plasma studies will get a lot out of them.

Microwave Oven Based Plasma Sources

Dr. Jones has had a considerable amount of experience with simple plasma sources based on oven components and several of these will be detailed.

Jones notes “Microwave plasmas are used as ion sources, for plasma chemistry, in ion implantation, isotope separation and in spectroscopy. 120 watt commercial units are available and sell for about $4000.” Unable to afford such a unit, Jones pursued several alternatives.

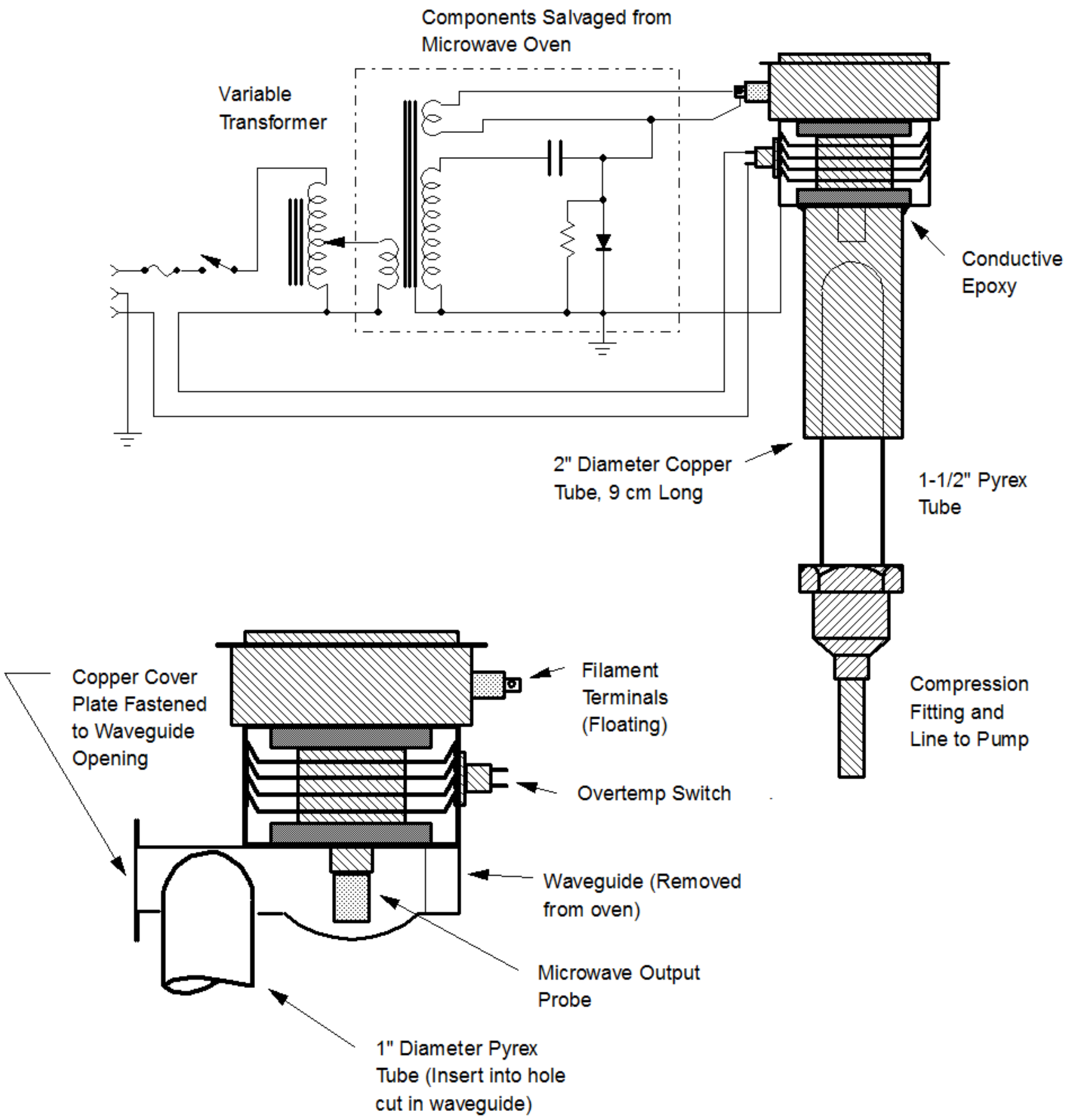
Referring to the figure on the next page, Jones states “In a typical microwave oven the magnetron tube is connected to the oven cavity via a waveguide formed out of folded sheet metal. In my microwave plasma source the 2M172J magnetron and power supply are removed from the oven along with a section of waveguide. The sheet metal section of waveguide (to which the 2M172J mounts) is cut from the oven proper and the open end of the guide is sealed closed with a folded sheet metal cap. This forms a microwave cavity 9 cm wide, 9 cm long and 3 cm thick. A hole is made in the cavity using a chassis punch. This hole enters the cavity from the side opposite to the face holding the magnetron. The hole is sized to the diameter of the Pyrex tube used as the discharge chamber. A 1” tube was used in the prototype and a standard lipless test tube may be used. A 1.5” tube would have the advantage of being able to mate with a 1.5” sink trap fitting. The tube is supported so that it is parallel to the magnetron’s probe.

"An alternative source was made by removing the magnetron entirely and attaching it with epoxy cement to a 9 cm long section of 5 cm diameter copper tubing, coaxial with the magnetron’s probe. The adhesive is preferably electrically conductive. However, it will also work with a poor electrical contact. The glass vacuum tube then slips down axially into this coaxial cavity.”

The figure also shows Jones’ simple power supply. A variable transformer is used to control the power to the tube. Normally the filament voltage is held constant but this would require another transformer. Throttling both the high voltage and the filament permits the power to be cut back to just a few watts. The tube, at full power, will put out over 600 watts. Striking the plasma requires much less power. Scaling back the power also reduces tube heating. Nonetheless, the overtemp protector should be left in the circuit. The cooling fan may be eliminated for low power, intermittent operation.

Depending upon the particular oven you pull apart, the circuit and components might differ somewhat. For example, in some ovens the resistor is paralleled with the capacitor and is in the same can. Fortunately, ovens generally have a schematic pasted to the inside of the cabinet.

If you wanted to eliminate all of the “plumbing” it is possible to make a plasma in a glass chamber simply by bringing the probe of a bare magnetron up to it. This is rather inefficient and there is more microwave leakage. Regarding this, Jones continues "I do worry about microwave leakage, particularly at high power. The cheap Rapitest (or similar) tester is a simple tool that can detect problems. But, even with the bare probe and with low power levels, the microwave level can be kept to safe levels a meter or two behind the magnetron."



The vacuum requirements for this sort of device are modest. Plasma reactors typically operate at a few Torr so even a single stage rotary pump will be effective. Jones has found that even a cheap metal water aspirator will work. This allows one to make a very cheap device.

In my experience, it is important to have a grounded metal screen in the coupling to prevent the possibility of radiation from being transported through the connecting line to the pump.

Furthermore, even if you lack any sort of vacuum pump, you can still do some interesting plasma experiments by exciting the gas within the aforementioned OA4-G tube as shown in the earlier figure.

Occasionally the discharge needs some help to get started. This can be done by "tickling" the discharge tube with a hand-held Tesla coil of the sort used for vacuum leak testing or with a high frequency TV flyback supply. I've used a gas grille piezoelectric igniter to good effect.

Jones concludes by saying "The rectangular cavity source is more efficient than the coaxial cavity source. With each of my microwave plasma sources there are component parts which could be optimized. For instance: What tube diameter is best? What length? And so forth. One could use a photo light meter (or a Langmuir probe) to judge which components give the most plasma for a given energy input. For the most part if something worked reasonably well I did not seek to optimize it. I just used it."

Some Additional Notes

The article Microwave *Discharge Atom Source for Chemical Lasers* by R.A. McFarlane (Review of Scientific Instruments, Vol. 46, August 1975, pg. 1063) deals with an oven-tube powered plasma discharge apparatus with a plasma tube that passes through the waveguide. Regarding safety the author notes, "Where the discharge tube left the waveguide structure, radiation levels of 10 mW/cm^2 were detected, falling rapidly to less than 1 mW/cm^2 at a distance of 15-20 cm. It is concluded that no hazard exists for normal operating procedures, but the experimenter should be aware that 10 mW/cm^2 is an upper limit to avoid cornea damage and some caution should be exercised when viewing the discharge directly."

The American Vacuum Society has a monograph on Langmuir probes. This is *Electric Probes for Low Temperature Plasmas* by David N. Ruzic, M-13, 1994. Unfortunately it is out of print but is available to AVS members as a pdf.

A resource that is freely available on line is *The use of dc glow discharges as undergraduate educational tools* by Stephanie A. Wissel, Andrew Zwicker, Jerry Ross and Sophis Gershman This was published in The American Journal of Physics 81 (9), September 2013. The link is https://www.reed.edu/physics/courses/Physics332.s17/pdf/Paschen%20Law.pdf

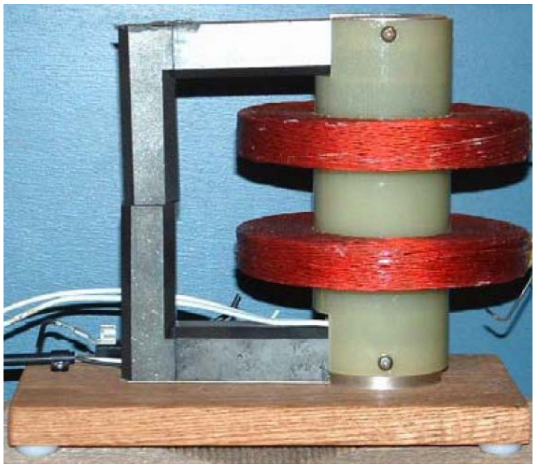
Miscellaneous Notes for DIY High Voltage Power Supplies

Flyback transformers with various transistor drivers have been used for a long time to produce high voltages for experimentation. Homebrewers have generally used oscillators of various types to drive the flyback using an added primary coil. This may also be done using the now common zero voltage switching (ZVS) modules. The newer flybacks have internal rectifiers as opposed to the "classic" flybacks that had an external vacuum tube or semiconductor rectifier.

I recently ran across the Chinese CO_2 laser transformers made by CloudRay. These are normally supplied as replacement parts for their line of laser cutters. These can be purchased as single units or with 2 or 3 tied in series (for the more powerful lasers). Each transformer has a 2x voltage multiplier at the positive end so they are limited to DC operation.

I obtained a set of three and separated one from the other two. I then tried driving it with a 12 volt lamp power supply of the type that transforms the 110 volt 60 Hz mains to 20 kHz. This appears to work well with the CloudRay transformer. The no-load output voltage is around 27 kV. I haven't measured the current capacity yet but it does produce a healthy spark. The specific model is the Amax HD150-120. It is rated at 150 watts. At Amazon, the set of CloudRay transformers runs about $32 and the lamp transformer is about $20.

The last issue of the print format *Bell Jar* (Vol. 10, No. 3/4), available on the *Articles* page, has an article that dealt with my experiments with high voltage implanter components and driving them with modified 12 to 120 volt inverters. In one configuration, I opened the inverter and added a pot to the SMPS IC's R_T pin so that I could adjust the 120 volt output frequency upward to over 400 Hz. The second variation was to simply disconnect the 120 volt/60 Hz output inverter stage and use the 180 volt 50 kHz output of the transformers to drive a modified implanter transformer. The transformer is shown below.



As noted in the article, the transformer has two secondary coils with a center tap. Each coil has 780 turns. I wound a new primary of 75 turns (vs. the original of 22 turns). When connected to a modified 400 watt inverter, the output is about 3500 volts, good enough for some vacuum and atmospheric pressure plasma work.

Vector has gone out of business and all of the newer inverters use surface mount components. The Vector inverters can be found on eBay but I purchased a couple of Bestek inverters. The modification is fairly simple – remove the surface mount diodes (4 in a bridge configuration) and tap into the AC input pads of the bridge. A 300 watt inverter produced a rather weak output using the above transformer. A 500 watt unit was much more satisfactory. At the full 500 watts, the 12 volt draw is specified as around 50 amps. My power supplies (normally used for my ham radio grea) are only 30 amps but the above transformer is within its limits.

Articles of Possible Interest in *Vacuum Coating & Technology* Magazine

Here is a selection of past articles that I have written on the subject of pump performance, pump speed and the relationship between speed, pressure and throughput ($Q=P\times S$).

July 2011
Boyle's Law and the Pump Down: Incremental Vacuum

August 2011
Measuring Pump Performance: Pump speed techniques and calculations

September 2011
Speed, Pressure and Throughput: Part 1 – System Diagnostics

October 2011
Speed, Pressure and Throughput: Part 2 – Managing Gas Flow in High Vacuum Systems

November 2011
Speed, Pressure and Throughput: Part 3 – Automating the Pressure Control Process

Articles may be accessed at http://vtcmag.com/. Scroll to the bottom of the page to the back issue selection box.

Impulse Measurements

With my various projects often involving fast high voltage pulses, I've finally come to the realization that my capabilities for voltage and current waveform measurement and analysis are woefully lacking. While good for many measurements, my 20+ year old PC oscilloscope is essentially useless for impulse work. With its parallel port interface, I couldn't even give it away. As a result, I'm in the process of upgrading with a proper sampling 'scope and learning about the practical aspects of current probes (Rogowski coils and current transformers), differential HV probes and fast voltage dividers. Some more details on that in the coming months.

Your Projects

The 10 volumes of the printed *Bell Jar* had a high proportion of reader projects. If you are working on something that is vacuum related that may be of interest to others, please contact me.

That's it for this month. Stay healthy!

Steve