THE EMERGENCE OF PLASMA PROCESSING

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References:

H. Abe, M. Yoneda and N. Fujiwara, Jpn. J. Appl. Phys. **47**, 1435 (2008)

V.M. Donnelly and A. Kornblit, J. Vac. Sci. Technol. **A31**, 050825 (2013)

Special thanks to: John W. Coburn

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OUTLINE

- The nanoelectronics revolution
- The emergence of plasma processing
- The evolution of etching discharges
- Future etch challenges

THE NANOELECTRONICS REVOLUTION

- Transistors/chip doubling every $1\frac{1}{2}$–2 years since 1959
- Billion-fold increase in performance for the same cost over the last 40 years

EQUIVALENT AUTOMOTIVE ADVANCE

- 60 billion miles/hr (90 $\times$ speed of light!)
- 20 billion miles/gal
- 1 cm long $\times$ 3 mm wide

EMERGENCE OF PLASMA PROCESSING

HUMBLE BEGINNINGS — SILVERING MIRRORS

- Sputtering discovered by Sir William Grove in 1852
- Relative sputtering rates of various metals measured in 1890–1910
- Crude apparatus used to sputter-coat silver, platinum, etc on glass surfaces
- The mechanism of physical sputtering was not understood
- Discharge state-of-the-art in the 1920's was rudimentary

10. " NOTE ON THE PRODUCTION OF MIRRORS BY CATHODIC BOMBARDMENT"

By F. SIMEON, B.SC., F.Inst.P.
(Messrs. Adam Hilger, Ltd.)

The production of mirrors by cathodic bombardment is not a new process. Workers with vacuum tubes since Grove, 1852, have noticed the bright deposit in the neighbourhood of platinum electrodes, which is more or less marked according to the current passed through the tube and nature of the residual gas. This deposit is generally objectionable, and was especially so in the case of the older form of X-ray bulb with platinum anti-cathode. This disintegration is not peculiar to platinum, nor indeed is platinum the most easily deposited metal. Sir William Crookes in 1891 investigated the relative rates of sputtering of a number of different metals under similar conditions of discharge. The relative rates are given in the following table, in which the rate for gold is taken as 100*

Palladium	108·80	Platinum	44·0	Iridium	10·49
Gold	100·00	Copper	40·24	Iron	5·50
Silver ...	82·68	Cadmium	31·99	Aluminium	0·0
Lead ...	75·04	Nickel	10·99	Magnesium	0·0
Tin ...	56·96				

Many other observers both before and since have investigated various points having some bearing upon this method. A bibliography of their papers will be found in the reference given.

A convenient apparatus consists of a vacuum tube of special form which permits of readily altering the cathode and of introducing and removing the various objects (glass plates, &c.) which it is desired to coat with a reflecting surface. The vessel employed in the apparatus exhibited is a vacuum dessicator, through the upper part of which is introduced, in addition to the exhaust tube for connection to the vacuum pump, two aluminium wires covered with glass tubing for insulation. To one of these, which is introduced centrally, can be attached a disc of the fine metal of which it is desired to form a mirror. The other, after emerging from the glass tube, is bent into a portion of a circle, in about the same horizontal plane as the surface to be coated, and so as to be as far removed from the surface as the vessel allows. These wires are connected externally to an induction coil, a Lodge valve also being included in the circuit. The article to be coated, after being scrupulously cleaned and dried, is placed upon a clean glass support in the lower part of the vessel. Connection between the two parts of the vessel is made with some form of vacuum grease, great care being exercised that neither the surface to be coated nor the cathode itself is in any way contaminated, as this will lead to some blemish in the final result. The vessel is exhausted until the cathode dark space extends nearly to the work

(From "The Making of Reflecting Surfaces", Phys. Soc., London, 26 Nov 1920)

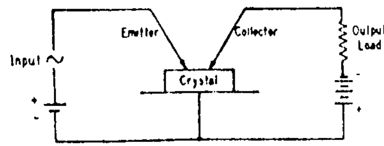
INVENTION OF THE TRANSISTOR — 1948

W.B. Shockley,
J. Bardeen,
W.H. Brattain

Nobel Prize in Physics (1956)

The "Transistor" – an Amplifying Crystal

THERE was a time in the early days of radio when the "oscillating crystal" could be catalogued with sky hooks, left-handed monkey wrenches and striped paint, because no one knew how to amplify a signal with a galena, silicon or other crystal. All this is changed by the recent Bell Telephone Laboratories' announcement of the "Transistor," a small germanium-crystal unit that can amplify signals, and hence be made to oscillate.



Housed in a small metal tube less than one inch long and less than a quarter inch in diameter, the Transistor has no filament, no vacuum, and no glass envelope, and is made up only of cold solid substances. Two "catwhisker"-point contacts are made to a surface of the small germanium crystal, spaced approximately 0.002 inch apart.

The Transistor shown is connected as an amplifier in the accompanying sketch. The contact on the input side is called the "emitter" and the output contact is called the "collector" by the Bell Labs. A small positive bias of less than one volt is required on the emitter, and the output circuit consists of a negative bias of 20 to 30 volts and a suitable load. The input impedance is low (100 ohms or so), and the output impedance runs around 10,000 ohms.

In operation, a small static current flows in both input and output circuit. A small current change in the emitter circuit causes a current change of about the same magnitude in the collector circuit. However, since the collector (output) circuit is a much higher-impedance circuit, a power gain is realized. Measuring this gain shows it to be on the order of 100, or 20 db., up through the television video range (5 Mc. or so). The present upper-frequency limit is said to be around 10 Mc., where transit-time effects limit the operation.

The Bell Labs have demonstrated complete broadcast-range superhet receivers using only Transistors for oscillator and amplifier functions (with a 1N34 second detector and selenium power rectifiers). An audio output of 25 milliwatts was obtained by using two Transistors in a push-pull connection. However, it seems likely that in the near future Transistors will find their maximum application in telephone amplifiers and large-scale computers, although their small size and zero warm-up time may make them very useful in hearing aids and other compact amplifiers.

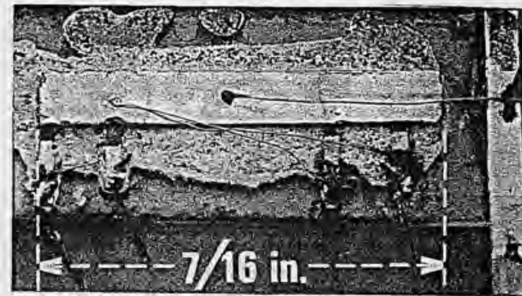
It doesn't appear that there will be much use made of Transistors in amateur work, unless it is in portable and/or compact audio amplifiers. The noise figure is said to be poor, compared to that obtainable with vacuum tubes, and this fact may limit the usefulness in some amateur applications. These clever little devices are well worth keeping an eye on. — *B. G.*

QST for October 1948

FIRST INTEGRATED CIRCUIT AND MICROPROCESSOR

Jack Kilby (1958)

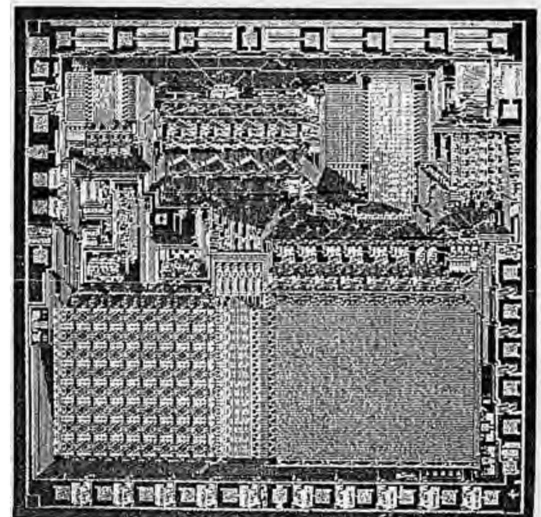
Nobel Prize in Physics (2000)



The first integrated circuit was made in 1958 by Jack Kilby of Texas Instruments.

Texas Instruments TMS 1000

USP 3,757,306 (1973)



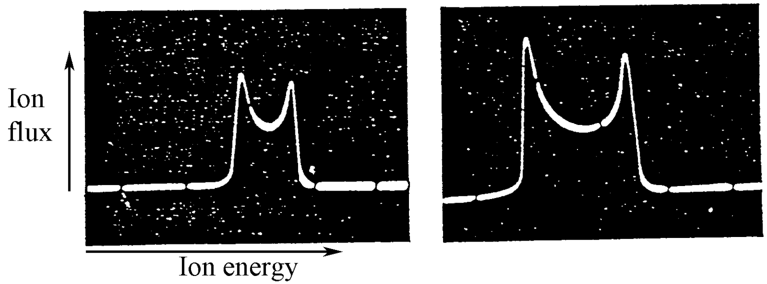
Less than two decades later, engineers put a complete microcomputer on a chip. (Source: Texas Instruments, Inc.)

SPUTTER DISCHARGE STATE-OF-THE-ART — 1960's

- Parallel plate capacitively coupled rf discharges that generated energetic ions were widely used for sputter-etching and sputter-deposition
- Formation of the ion energy distribution on substrate surface
- Role of blocking capacitor and formation of self-bias voltage
- Influence of electrode area ratio on dc plasma potential
- Optical emission spectroscopy for etch end-point detection
- Reactive sputter deposition
- Basic theory of physical sputtering

EXAMPLES

- Earliest measurement of ion energy distribution (J. Erö, 1958)



- Blocking capacitor and self-bias voltage (Butler and Kino, 1963)

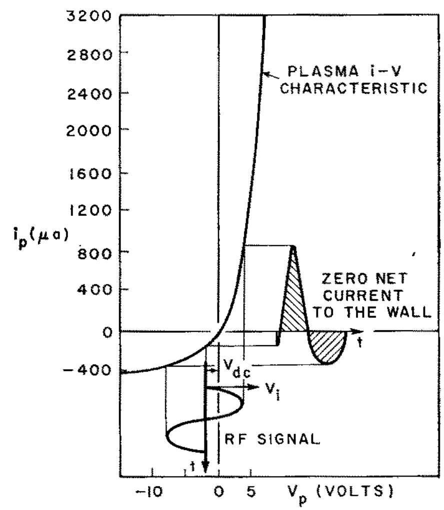


FIG. 2. Pictorial representation of mechanism by which a positive ion sheath is formed as a result of applying an rf voltage outside the plasma.

PLASMA ETCH STATE-OF-THE-ART — 1970's

- Etch was isotropic
- Capacitively-powered "barrel" etchers were mainly used
- High pressures ($\sim$ 1 Torr)
- An important application was photoresist strip
- Isotropic etching of Si, W, Ta, Ti, Si_3N_4 was demonstrated
- Need for volatile etch products was recognized
- No mention of energetic ion bombardment

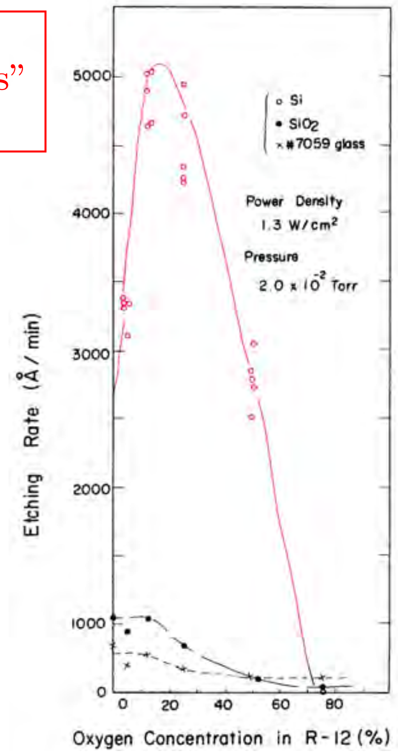
ION-ENHANCED PLASMA ETCHING

- Sputtering — involatile products and high ion energies
- Plasma etching — volatile products and low ion energies

Who first combined volatile products with high ion energies?

N. Hosokawa, R. Matsuzake and T. Asamaki
"RF Sputter-Etching by Fluoro-Chloro-Hydrocarbon Gases"
Jpn. J. Appl. Phys. Suppl. 2, Pt. 1, 435 (1974)

Sputtering gas: Symbol	Sputtering gas: chemical composition	Etching rate
	A	124 Å/min
	C_2HCl_3	330
R-14	CF_4	900
R-11	CCl_3F	1670
R-12	CCl_2F_2	2200
R-21	$CHCl_2F$	410
R-22	$CHClF_2$	1430
R-112	$(CCl_2F)_2$	1280
R-113	CCl_2FCClF_2	2015
R-114B2	$(CBrF_2)_2$	1850



IMPLICATIONS OF HOSOKAWA'S DISCOVERY

(From discussions with John W. Coburn)

- The work was first presented at the Sixth International Vacuum Congress, Kyoto, Japan, 25-29 March 1974
- Hosokawa's main interest was to etch faster
- He may not have recognized the importance of his discovery for pattern transfer
- But there were many pattern transfer engineers in the audience
- In 1975, there were around a dozen "reactive ion etching" (RIE) patents filed worldwide

ANISOTROPIC PLASMA ETCHING WAS BORN

SILICON DIOXIDE AND ALUMINUM ETCHING

- Anisotropic etching of SiO_2 with high selectivity over Si

R.A.H. Heinecke, "Control of Relative Etch Rates of SiO_2 and Si in Plasma Etching," Solid State Electronics **18**, 1146 (1975)

Typical Etching Rates in C_3F_8 Discharge

SiO_2 thermally grown	2000 Å/min
Si	≤400 "
Silox densified	2000 "
Silox phosphorus doped	3-4000 "
Si_3N_4	≥6000 "

Etching conditions

Etching gas	C_3F_8, CP grade 99%
Pressure	0.3 torr
Pumping speed	90 l/min
Leak rate	<0.01 torr/min
Susceptor	Stainless steel, water cooled.
Plasma current density	6mA/cm^2
Frequency	1 MHz

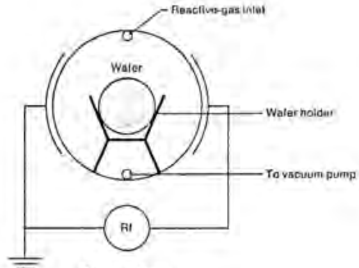
- Anisotropic etching of Al with native Al_2O_3 etch

S.I.J. Ingrey, H.J. Nentwich, and R.G. Poulsen
"Gaseous Plasma Etching of Al and Al_2O_3"
USP 4,030,967 (filed 1976)

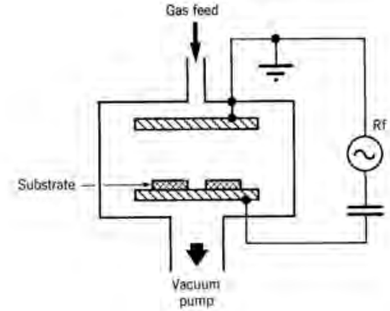
EVOLUTION OF ETCHING DISCHARGES

THREE GENERATIONS OF ETCHING DISCHARGES

FIRST GENERATION
(1 source, multi-wafer, low density)

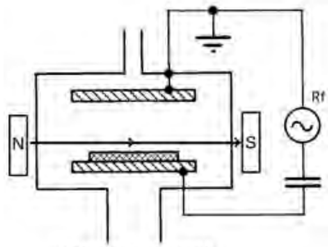


Barrel etcher
(Isotropic etch)

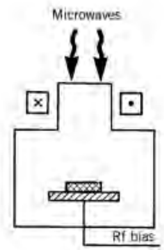


Capacitive
(Anisotropic etch)

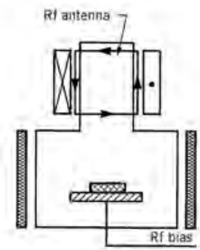
SECOND GENERATION
(2 sources, single wafer, high density)



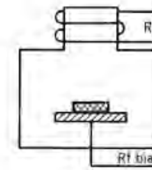
Magnetically enhanced
capacitive discharge



ECR

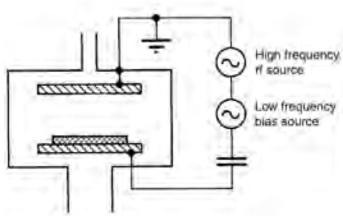


Helicon

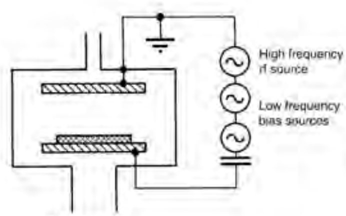


Inductive

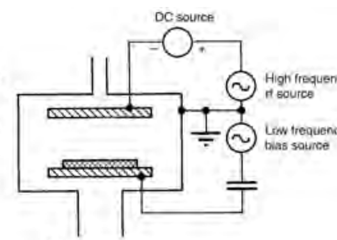
THIRD GENERATION
(multi-source, single wafer, moderate density)



Dual frequency
capacitive discharge



Triple frequency
capacitive discharge



DC/dual frequency
capacitive discharge

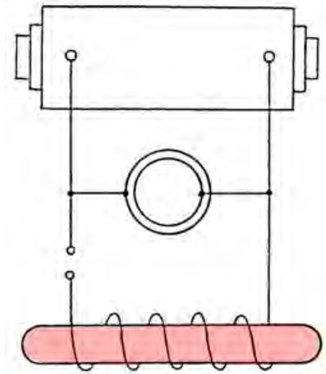
HIGH DENSITY INDUCTIVE DISCHARGES

MOTIVATION

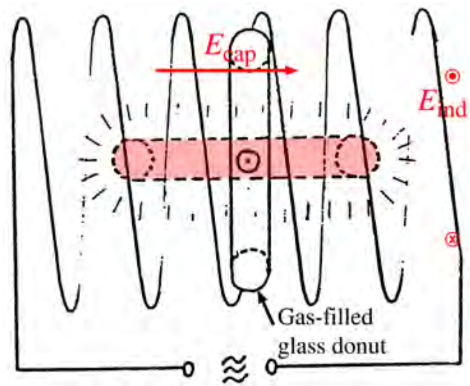
- High density (compared to capacitive discharge)
- Independent control of plasma density and ion energy
- Simplicity of concept
- RF rather than microwave powered
- No source magnetic fields

EARLY HISTORY

- First inductive discharge by Hittorf (1884)

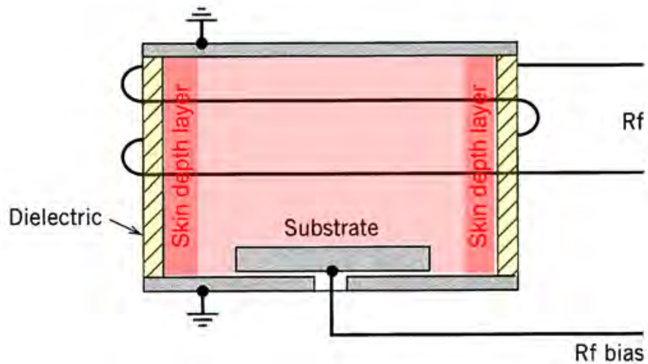


- Arrangement to test discharge mechanism by Lehmann (1892)

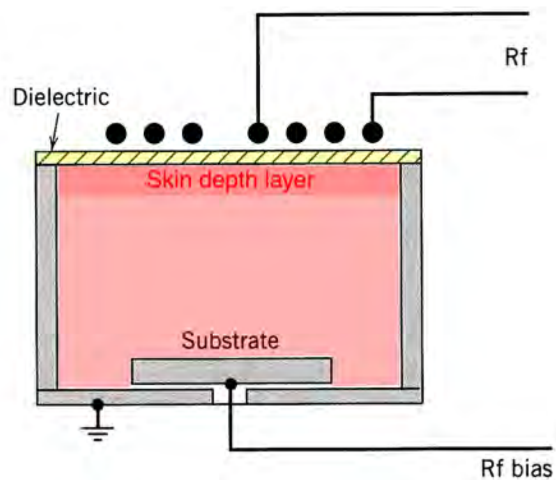


CYLINDRICAL AND PLANAR CONFIGURATIONS

- Cylindrical coil



- Planar coil



MICROWAVE DISCHARGES, PULSING, AND ELECTRONEGATIVE GASES

HIGH DENSITY PULSED MICROWAVE DISCHARGE

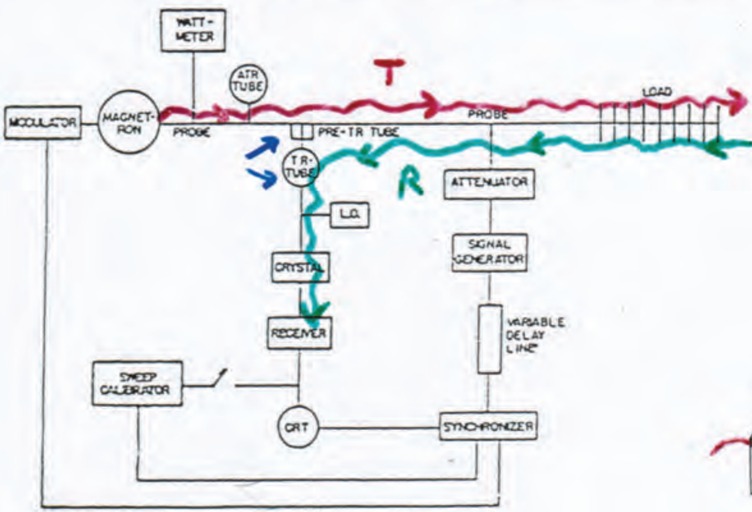
PHYSICAL REVIEW VOLUME 70, NUMBERS 5 AND 6 SEPTEMBER 1 AND 15, 1946

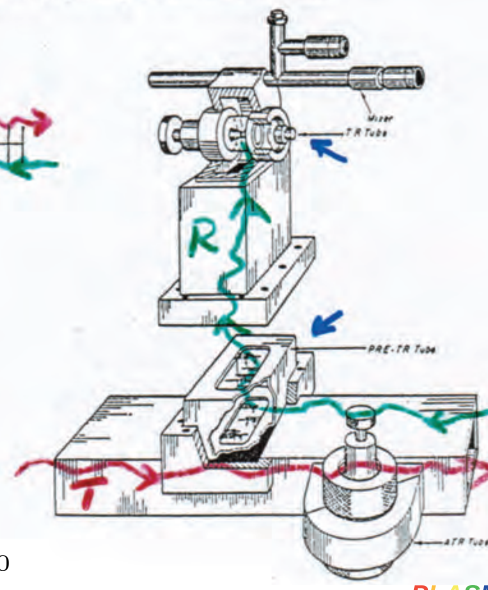
Physical Processes in the Recovery of TR Tubes[1]

H. Margenau,[2] F. L. McMillan, Jr.,[3] I. H. Dearnley,[4] C. S. Pearsall,[5] and C. G. Montgomery[2]
Radiation Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts

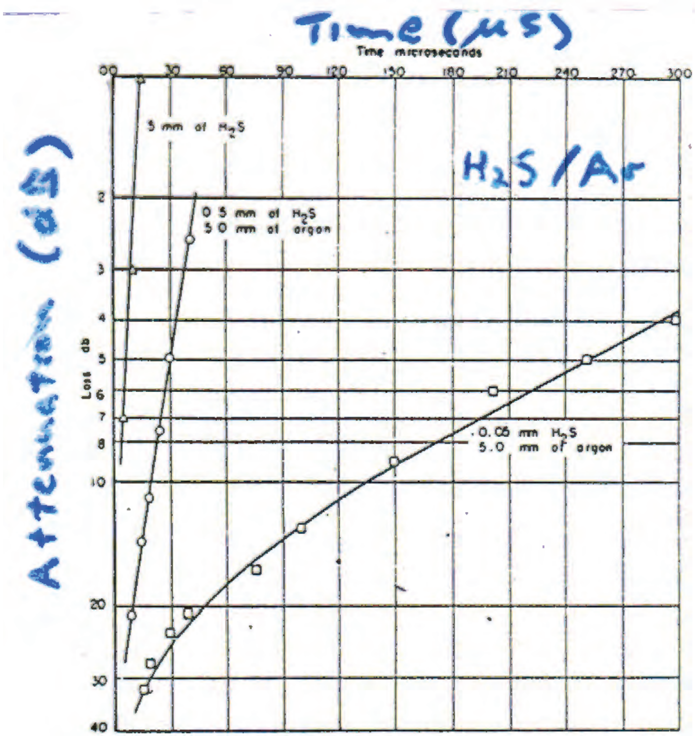
(Received May 3, 1946)

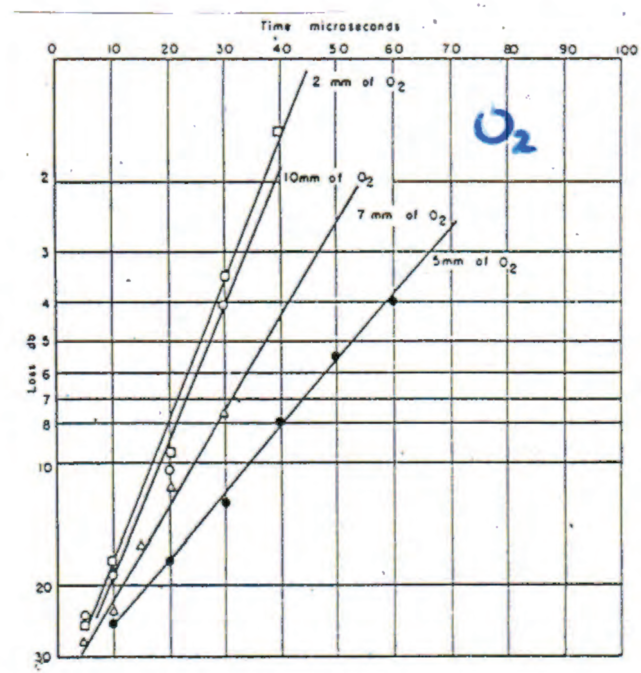
Gas-filled switching (TR) tubes are important components of a radar duplexer. The recovery of the tube, i.e., the elimination of ions on termination of the discharge, is of great interest because it determines the quality of radar reception. In the first part of this paper, techniques of measurement of the recovery of certain types of TR tubes are described and results are reported. In the second part, the physical processes responsible for recovery are discussed in connection with simple theoretical developments concerning recombination of electrons and positive ions, diffusion of electrons, and capture of electrons by gas molecules. The last of these processes is found to be of principal importance in removing electrons and producing a short recovery time.





ELECTRONEGATIVE DISCHARGES (Ar/H_2S, O_2)





- Attaching gases soak up electrons fast

FUTURE ETCH CHALLENGES

- New materials and structures
- For 10 nm CD, must control accuracy to ± 1 nm (1.8 lattice constants!) across 450 mm wafer
  $\Rightarrow$ Gentle and precise etches

RESPONSES

- Evolutionary: more "knobs" on "existing" tools
  — Multiple driving frequencies/dc/magnetic fields etc
  — Segmented electrodes/driving coils/chucks etc
  — Many pulsing duty cycles, frequencies etc
  $\Rightarrow$ Tight control of electron, ion and photon energy distributions and fluxes
- Revolutionary: atomic layer etching and neutral beam etching

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