DEVELOPMENT OF INTEGRATED THERMIONIC CIRCUITS FOR HIGH-TEMPERATURE APPLICATIONS*

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Abstract

This report describes a class of devices known as integrated thermionic circuits (ITC) capable of extended operation in ambient temperatures up to 500°C. The evolution of the ITC concept is discussed. A set of practical design and performance equations is demonstrated. Recent experimental results are discussed in which both devices and simple circuits have successfully operated in 500°C environments for extended periods of time.

Approach

The approach taken for ITC active devices has been to use the intrinsically high-temperature phenomenon of thermionic emission in conjunction with thin-film integrated-circuit technology to produce microminiature, planar, vacuum triodes. The resulting technology uses photolithographically delineated thin films of refractory metals and cathode material on heated, insulating substrates. Typical geometries and dimensions are shown in Fig. 1. Many such devices are simultaneously fabricated on a single substrate, giving high packing density. The integrated grid-cathode structures are intrinsically rugged.

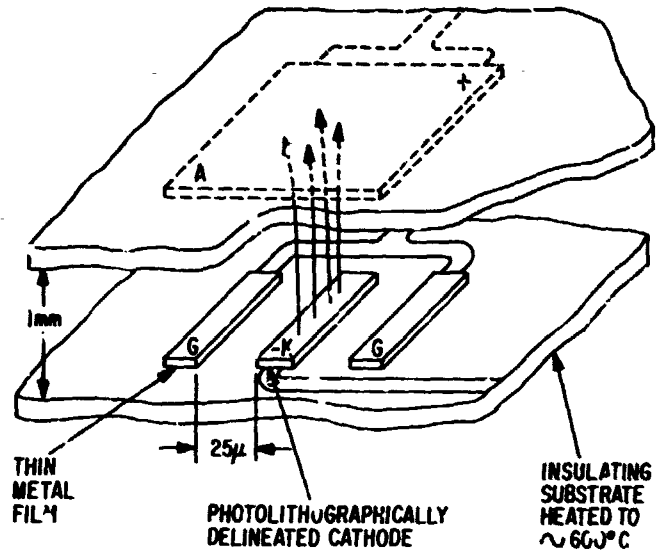

Fig. 1. Basic ITC gain device.

The ITC Structure

Notice in this structure, the anode is in the natural path of the electrons, and the closely interdigitated grids and cathodes are used to maximize grid control. In a sense, this structure is like a standard triode with the grid moved down into the plane of the cathode. In fact, it has been shown through computer simulation and experimentally verified that the fundamental equation governing conventional triode performance may be used to describe the performance of an ITC device.

$$I_p = K\left(V_g + \frac{V_p}{\mu}\right)^{\frac{3}{2}} \tag{1}$$

where I_p is the place current,

V_g is the grid voltage,

V_p is the plate voltage,

μ is the amplification factor, and

K is a constant called the perveance.

Furthermore, from electrostatic analysis it has been shown that for a device with grid width, cathode width, and grid-to-cathode spacing equal to a and cathode-to-anode spacing equal to d,

$$\mu \cong 0.5611\,\frac{d}{a} - \frac{1}{2}\ . \tag{2}$$

Thus, μ, the electrostatic amplification factor, is linearly related to the ratio d/a, with no other geometrical factors. This result is remarkably similar to that obtained for a conventional triode. Therefore, depending on the circuit application, the desired amplification factor can simply be selected by determining d/a.

A similar analysis for the device shown in Fig. 2, where a is the width of the cathode, b the distance between the grid and cathode, c the width of the grid, and d the distance between plate and cathode, results in

$$\mu = -\left(\frac{b + c}{a + 2b + c}\right) - \frac{d}{b}\sum_{n=1}^{\infty}\frac{2\pi}{n}\left(\cos\frac{n\pi(a + 2b)}{a + 2b + c} - \cos\frac{n\pi a}{a + 2b + c}\right), \tag{3}$$

which can easily be summed on a calculator.

Device Processing

To date, device processing has been the most emphasized portion of the ITC development program.

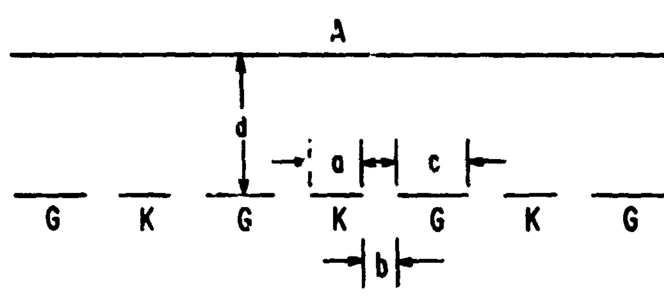

Fig. 2. Unequally spaced device.

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Sapphire was chosen as the substrate material for ITC devices because of its high quality surface finish and high electrical resistivity at high temperatures ($\cong 8 \times 10^7$ Ω-cm at 800°C).

Figure 3 is a side view of the ITC metalizations on the circuit or device side of the substrate.

Notice that all the metals are refractory because of the need to withstand high-temperature environments. (This is in contrast to the gold and aluminum used in conventional silicon integrated circuits.) The bond pad is platinum, and the platinum bond wires are attached by parallel-gap or ultrasonic wire bonding. The base metal under the cathode is tungsten.

The cathode coating technique was developed by Geppert, Dore, and Mueller at Stanford Research Institute in 1969. This technique uses photoresist mixed with oxide cathode coating, which is then delineated photolithographically.

In practice, the cathode coating is spun onto the wafer and delineated like photoresist. The circuit is then packaged and placed on a vacuum pump. The package is evacuated and the cathode coating activated by applying power to the heater until the substrate approaches 900°C.

During normal operation, the heaters are used to heat the substrate to 750-800°C in order to provide acceptable electron emission from the cathode (>100 mA/cm²).

<u>Current Technology and Limitations</u>

Figure 4 is a picture of the first Los Alamos ITC device, manufactured in 1977. The lines and spaces are 5 mils. The heater pattern is visible on the back of the sapphire. The darker fingers are the cathodes.

Figure 5 is an array of three devices from 1979. The cathode and grid lines are 1 mil, and spaces between grids and cathode are 0.2 mil.

Because the oxide cathode is granular in nature (with crystals on the order of 1 μm), the 0.2 spacing appears to represent an optimal limit to device size.

This technology yields a minimum device size of approximately 10 by 3.5 mils, which is enough to hold over 12,000 devices on a pair of 3/4-in.-diam sapphire substrates. As will be described later, factors other than minimum device size currently limit the useful density of devices on a substrate.

High-Temperature Operation

The 400°C and 500°C Operations to Date

The high-temperature operation tests conducted to date fall into two categories by time frame and package material. The run September 1979 through February 1980 used the stainless steel (302) or Kovar envelope materials. High-temperature vacuum feedthroughs using stainless steel, aluminum, and high-temperature brazes were designed for these packages by Ceramaseal Corporation, New Lebanon, New York. Initially, these packages had problems with the evolution of manganese, iron, and chromium, (in the form of diatomic oxides, for example Mn_2O_3), plus the liberation of gases at higher temperatures. As a result, these tests, described in the upper portion of Table I, should only be considered preliminary. Even so, the 400°C test device operated successfully for over 7000 hours. A number of simple circuits were also run in high-temperature environments using these initial packages.

CATHODE COATING APPLIED AND DEFINED PHOTOGRAPHICALLY

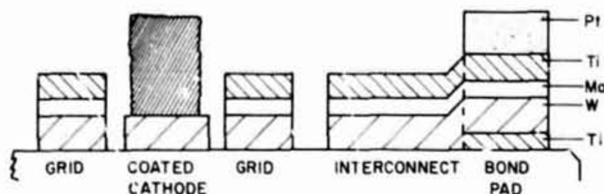

Fig. 3. ITC metalization and photolithography.

Fig. 4. First Los Alamos ITC device (1977).

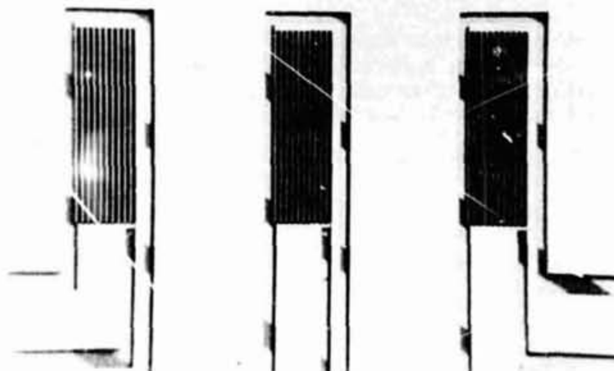

Fig. 5. Three triodes (1979).

TABLE I

HIGH TEMPERATURE LIFE TEST SUMMARY - 1st SERIES

Temp.	Start Date	Hours	Type	Bulb Material	Comments
400°C	9-26-79	7750	Triode	Kovar	No appreciable degradation through 6000 hours; emission loss thereafter stopped at 80% loss.
500°C	9-27-79	1608	Amplifier (2-device)	Kovar	Stopped - gain of 1; individual tests indicated emission loss.
500°C	9-17-79	2590	Triode	Kovar	No emission degradation through 2000 hours; increasing gas load, emission loss thereafter stopped at 50%.
500°C	10-18-79	430	Triode	Kovar	Stopped - loss of emission.
500°C	10-4-79	4464	Triode	S.S.	No degradation through 4000 hours; emission loss thereafter stopped at 50% loss.
600°C	9-20-79	328	Triode	Kovar	Stopped - loss of emission.
500°C	11-2-79	1070	Differential amp (6-device)	Kovar	Stopped - decreasing gain; electrical leakage on substrate.
500°C	11-7-79	6144	Triode in Ti jig	Kovar	Gradual decline in emission with increasing gas loads after 2000 hours; stopped at 50% loss.
500°C	1-31-80	588	5-MHz oscillator	Kovar	Oscillation stopped; electrical leakage on substrate.
500°C	2-19-80	816	5-MHz oscillator	Kovar	Oscillation stopped; electrical leakage on substrate

The above tests have all been terminated. Following tests are ongoing using high-purity nickel bulbs and "clean" welding techniques.

HIGH TEMPERATURE LIFE TEST SUMMARY - 2nd SERIES - IMPROVED BULB

Temp.	Start Date	10-8-80 Hours	Type	Bulb Material	Comments
500°C	5-9-80	3648	Triode	Ni	No degradation in emission; no leakage.
550°C	7-8-80	2208	Triode	Ni	Valved off pump to facilitate gas burst tests; developed loops. Burst test at 1400 hours indicated argon present; evidence of gas cleared and did not

In all cases, failure was due to electrical leakage on the substrate because the metals were being liberated from the package. The 5-MHz Hartley oscillator operated with both the capacitor and inductor at 500°C.

With the understandings evolved from the stainless steel and Kovar tests, a newer package was designed using nickel. The first test began May 19, 1980, and is still running after 6312 hours. Figures 6 and 7 show the device characteristics on May 19 and October 9. The device characteristics are virtually unchanged.

The second test, also ongoing, uses a device operating at 550°C; the device is valved off the pump to allow periodic gas-burst tests. This device is still being evaluated after 2200 hours. The results are tentative because no signs of gas have been seen in the characteristics after the 1400-hour gas burst.

Conclusions Regarding High-Temperature Operation

Based on the tests performed to date, ITC technology has demonstrated the ability to operate

Fig. 6. Improved package (500°C) first day.

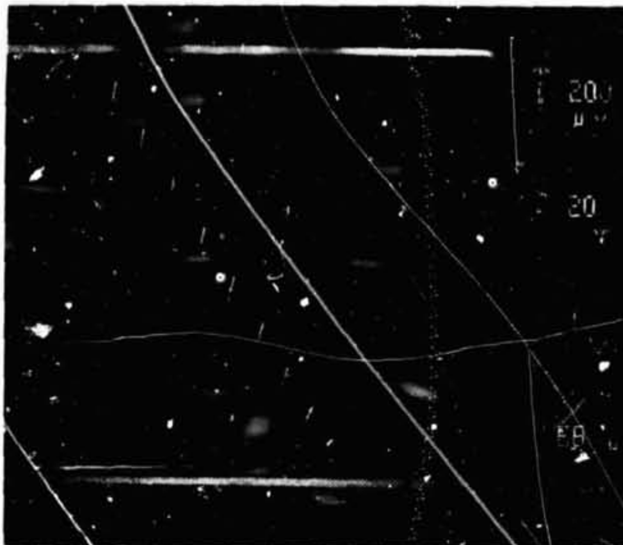

Fig. 7. Device (500°C) after 3600 hours.

successfully and reliably for thousands of hours at temperatures up to 500°C. This temperature is not the fundamental limit for ITC devices, and with the evolution of better gettering techniques (more complex than titanium) and packaging techniques (perhaps glass-ceramic - reference paper to be given at this conference by Dr. Cliff Ballard, Sandia Laboratories), higher temperature operations are expected in the future.

Circuits

The design of ITC circuits is in many ways similar to the design of conventional integrated circuits. Therefore, ITC design techniques use the advantages gained from the simultaneous fabrication of many devices on the same substrate. The inherent matching of device characteristics and the tracking of these characteristics over temperature and life are exploited. Functional circuit elements such as differentional stages, current sources, and circuits that use active devices as loads have been fabricated using discrete ITC devices, and their performance has been verified against theory. The simple active load, shown in Fig. 8, is particularly valuable because its gain

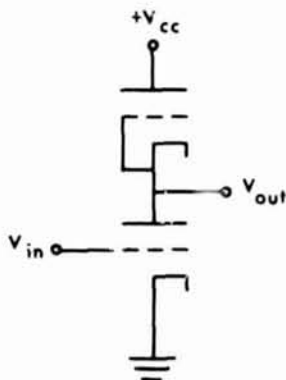

Fig. 8. Gain stage with active load.

$(-\mu/2)$ is only dependent on device geometry, the ratio of line width to cathode-anode spacing. Therefore, the gain of the stage is independent of the transconductances of the two devices and, hence, of the operating temperatures.

As a result of the success of designing functional ITC circuits using discrete devices, the design of integrated ITC circuits has become the recent emphasis of the program. Because these efforts are ongoing, this section will mainly contain general comments and directions for future work.

The design of integrated circuitry with complex functions on a single pair of substrates presents new challenges and possibilities as a result of device matching and, unfortunately, some problems, in particular, electrostatic interactions between devices.

Figure 9 schematically depicts the origin of such interactions.

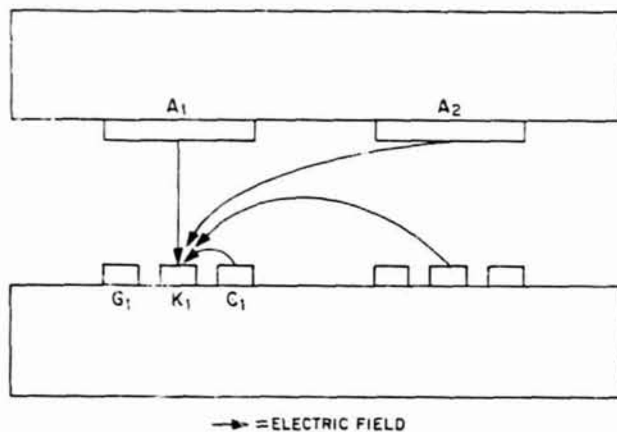

Fig. 9. Electrostatic interactions.

The key to increasing the functional complexity and maximum gain on a single substrate pair will be the development of appropriate techniques for making design tradeoffs between device layout (position on the substrate) and circuit function.

Although results are still tentative, Figs. 10 and 11 show the layout of one experimental pair of substrates for a differential gain stage. In current experiments, a series of device masks are used to photolithographically generate an array of devices, which are then interconnected using a series of masks with line segments. Results suggest that a reasonable 2-year goal for ITC technology is the design of an operational amplifier with a voltage gain of 1000 or more on a pair of 0.75-in.-diam substrates.

Conclusions

Based on the results described above, the future for ITC technology is bright. Programmatic efforts have led to an ITC technology with demonstrated high-temperature capability (500°C for thousands of hours) and to fabrication techniques commensurate with mass production. Physical models and detailed device understandings have been developed. Preliminary circuits using discrete devices, single not integrated, have demonstated the potential of ITCs. All that remains is the final development of integrated circuit

design techniques and the demonstration of integrated circuity.

The results of the ITC development program suggest that ITCs may become an important technology for high-temperature instrumentation and control systems in geothermal and other high-temperature environments.

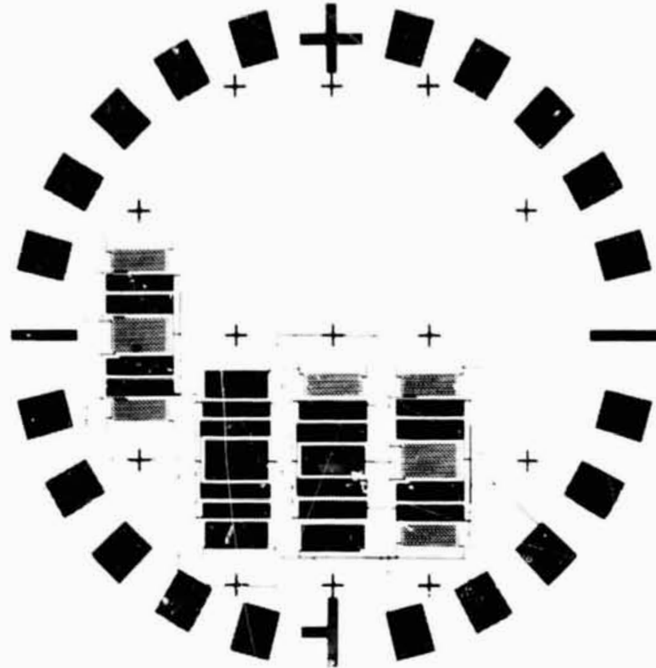

Fig. 11. Substrate 2, differential gain stage.

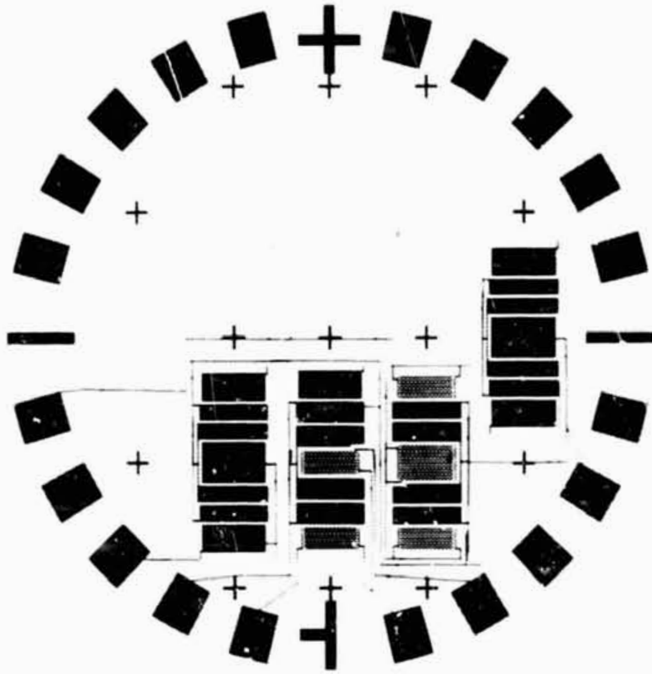

Fig. 10. Substrate 1, differential gain stage.