

*Intelligence needs impel giant advances
in micropowered microelectronic systems.*

MICROTECHNOLOGY

Donald Reiser
and
Harry Wood

It can be said that in general ideal intelligence collection systems perform best when placed as close to the target as possible. This certainly was the principle adopted by the ancients in their liberal use of harlots as informers. But in the absence of a desire on the part of the target to have it in close proximity, the collection system needs a completely different set of qualifications. To list but a few of the more obvious, it must operate in a hostile environment, be as undetectable as possible, have an extremely long life, and provide reliable, high-quality information. These general requirements apply to audio, video, optical, and electronic intelligence gathering systems. A common need among all such systems is for minimum size and weight. And the satisfaction of this need often entails a requirement for micropower as well.

Micropower, as the term implies, is the operation of equipment with greatly reduced power drain.¹ Minimizing power needs vastly simplifies the size and weight problem by eliminating bulky power supply components. It is also possible to turn the coin over and say that for a given power supply a greatly enhanced capability and reliability can be obtained from micropower operation; more functions can be performed and redundancy provided by the same amount of energy. Thus micropower operation will improve any system, whether airborne, animal- or man-borne, or permanently installed, whether the power source is a battery, a generator, or a solar cell.

Intelligence Initiative

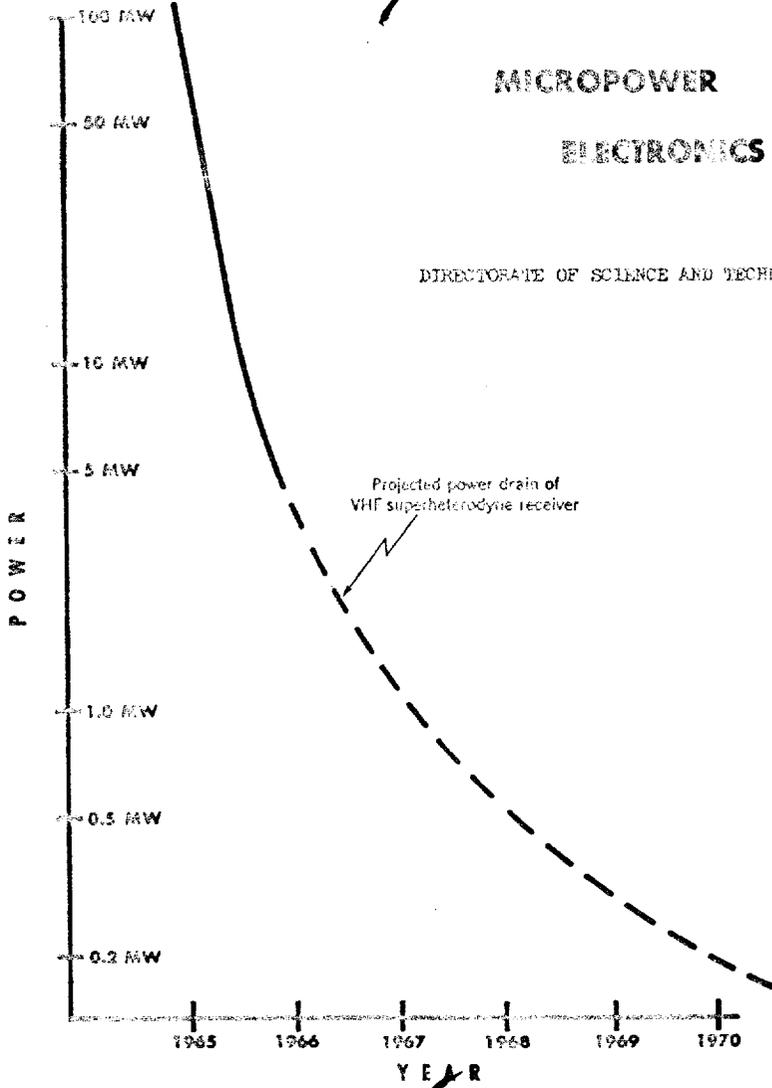
In mid-1965 the authors made a survey of eighteen top U.S. microelectronic firms to determine the current status of micropower technology. The results were of sufficient interest to warrant a staff paper on micropower and microelectronics in handbook form. The cover

¹The prefix micro is appropriate both in its general sense of "very small" and in its precise scientific usage as one of the series micro=a millionth, nano=a thousandth of a millionth, and pico=a millionth of a millionth. Some have suggested, indeed, that the nanopower stage is not far in the future.

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MICROPOWER ELECTRONICS

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Figure 1.



of that handbook is reproduced in Figure 1. It shows the power drain in milliwatts of a VHF superheterodyne receiver projected from 1965 to a date in 1970. The rapidly falling curve was based on estimates of the improvement that could be made in industrial technology over this span of time if the effort received sufficient emphasis. Up to 1968 it indicated a reduction in the power required for this representative complex receiver from as much as 50 mw to as little as 0.5 mw, two orders of magnitude. It is extremely gratifying to be able to state that this is in fact the nature of the progress that has been made.

On the basis of the 1965 findings CIA approached the Advanced Research Projects Agency with a proposal to sponsor accelerated micro-power development, and ARPA agreed to divert substantial funding to the program. An arrangement was established with three selected contractors under which the government would contribute fifty percent of the costs. Calculations at that time showed that power efficiency could theoretically be improved by seven or eight orders of magnitude, while only three to five were necessary for the results desired in many advanced intelligence devices. Improvement by five orders of magnitude would permit important systems to operate on ambient power, that is on the light, heat, radiation at radio frequencies, etc. available in the environment.

One of the keys to microtechnology is the practice of building electronic devices and circuits with thin deposits or diffusions of conducting or semiconducting material on the surface of wafers, but progress in minimizing the size of these requires a corresponding maximizing of precision in the fabrication. We shall not treat here the details of improvements in the industrial processes—photo-etching, controlled deposition, surface cleanliness control, etc.—that are being achieved. Broadly, the requirement is for advances in the following fields of solid-state technology:

- Fabrication of very small active devices (notably transistors) through improved topography, masking, etc.
- Low-parasitic isolation and interconnection (the elimination of unwanted by-product frequencies in the circuits)
- Surface characteristics
- Structure control
- Ultimately, development of new materials.

Micro Transistors

The field of microelectronics was born with the advent of the transistor in the early 1950's. Operating voltages dropped, the size of devices became significantly smaller, and there was motivation to reduce the over-all size of most passive electronic components also.

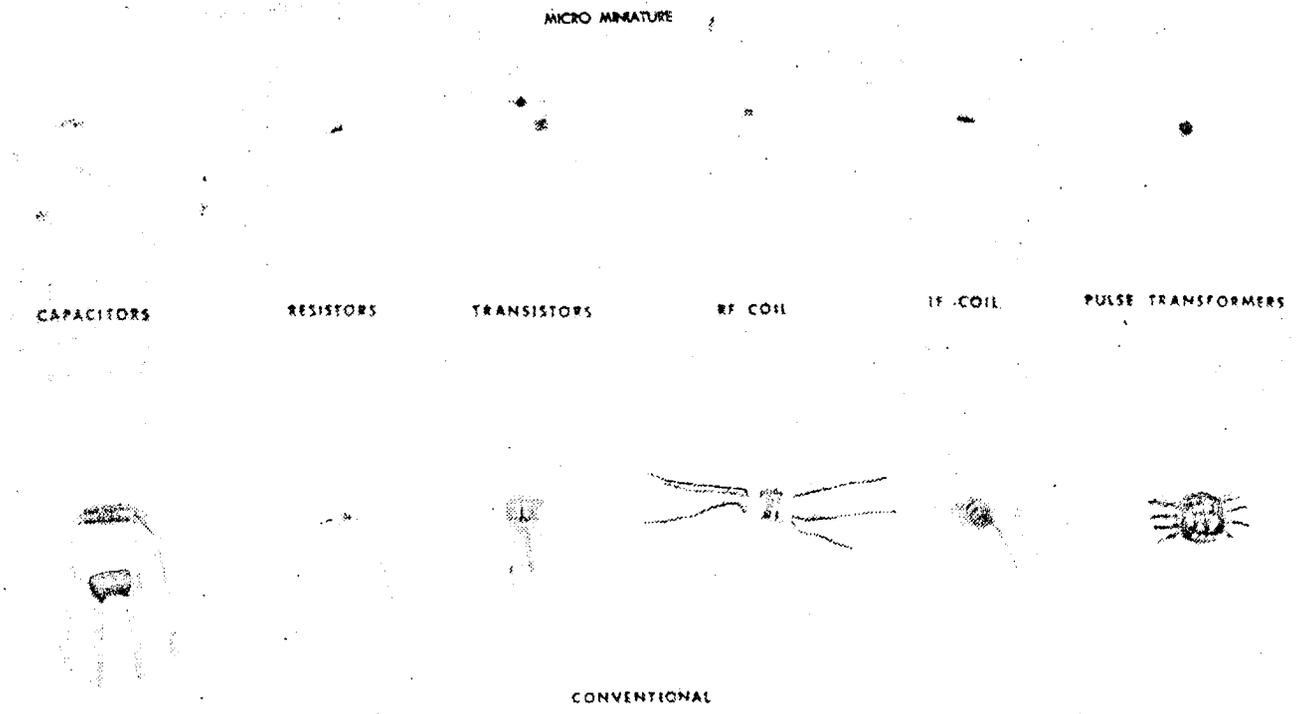


Figure 2.

Starting with very modest beginnings by researchers at Bell Labs, transistor technology progressed from the crude audio-frequency devices of that era to the high-frequency transistors of the early 60's.

Along with this growth in transistor technology, an industrial complex based on a concept of all solid-state electronics came into being. All manner of electronic components were redesigned, the new differing radically from the old primarily in size. See Figure 2. Number 24 wire (20 thousandths of an inch in diameter) gave way to one mil metalization (a metal layer one thousandth of an inch thick) for interconnection between devices. One no longer manipulated circuits by hand but packaged them complete in containers such as the "flat pack" and the "TO-18 can." Figure 3 illustrates such packaging.

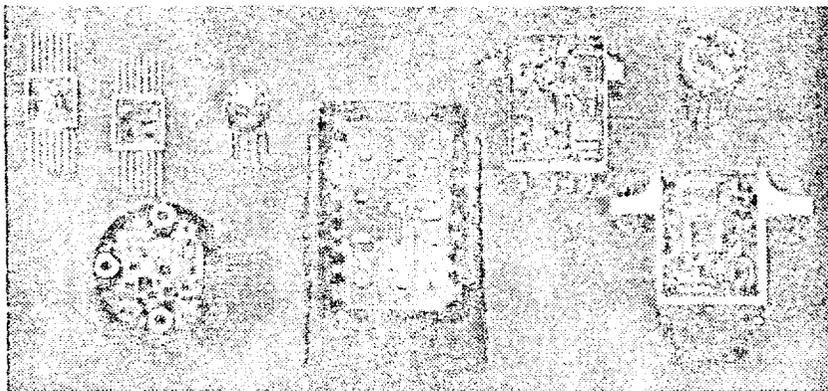


Figure 3. Various packages each holding a complete electronic circuit. Flat packs are at upper left, the TO-18 at upper right.

This new technology had immediate applications in intelligence; size reduction obviously satisfied a pressing need to make surveillance devices much more unobtrusive. As solid-state technology provided circuit functions which could be packaged in increasingly high-density microminiature form, the projection of a million components per cubic inch was not out of the question from a size point of view. But if each of these components used a milliwatt of power there would be dissipated a kilowatt of heat in that same cubic inch—a situation undesirable to say the least. Heat dissipation per unit volume was what limited the useful application of microminiaturization. Thus the development of microelectronics led directly to that of micro-

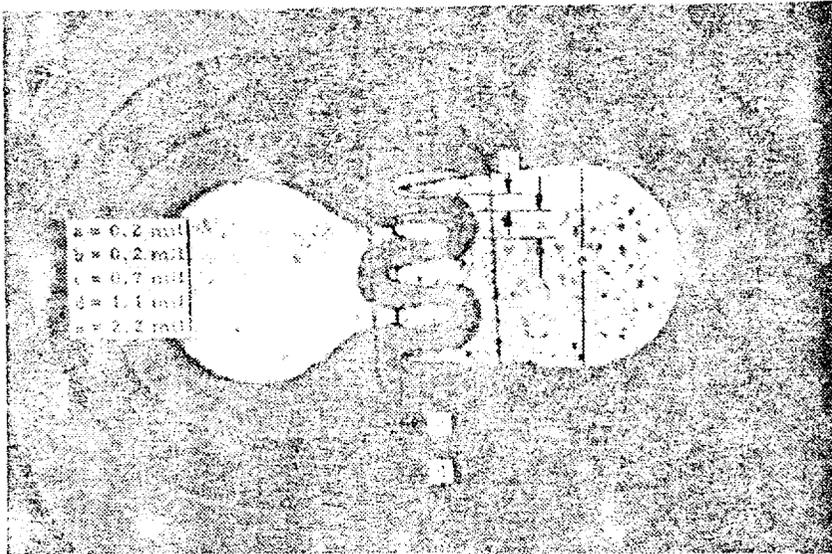


Figure 12. 1965 transistor.

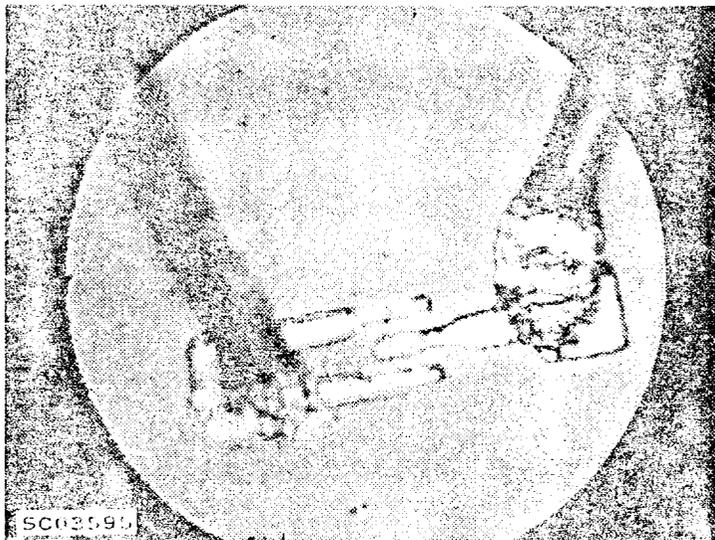


Figure 13. Current device.

most self. Note particularly the linear edge and uniformity of these stripes and their superior alignment within the window. These are the reasons for the improvement in performance.

Figure 14 shows the achievement of the counterpart elements for the next advanced micropower transistor. The characteristic fingers here are one micron wide and the space between them is also one micron. This structure, fabricated with the new projection masking system, constitutes the smallest transistor elements fabricated to date. It is planned to integrate this projection masking system into the over-all micropower program and begin the regular production of transistors of this size. We are budgeting research and development funds to produce two prototypes of the optical system for delivery to two principal micropower transistor developers so that they can make these smaller devices.

There are many other facets of the effort to improve the performance of micropower devices; but the technique for size reduction and improved precision discussed above, which has yet to be employed, illustrates how we can achieve some of the advances needed to narrow the gap between existing capabilities and the theoretical limit.

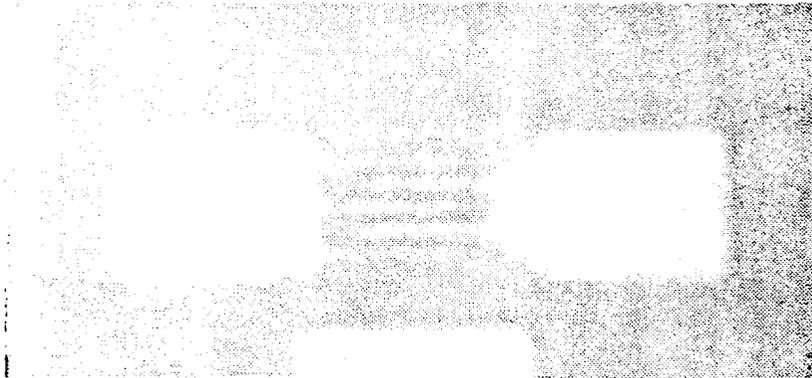


Figure 14. Latest advance.

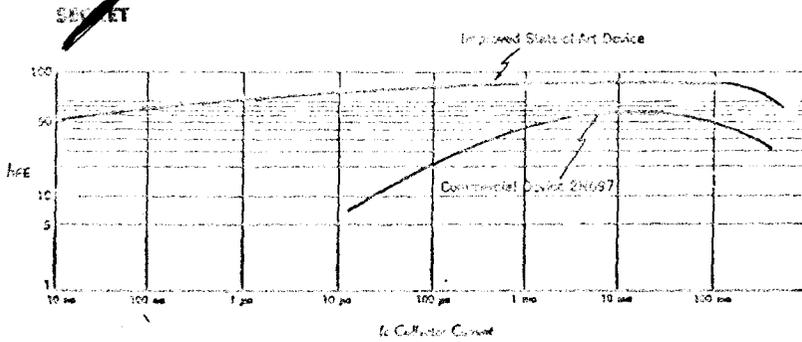


Figure 4. Early measurement shows micropower transistor performing as well at less than 100 nanoamperes as its commercial counterpart at about 12 millamps.

power— or, to group the two together under a single designation, to microtechnology.

The development of micropower systems was approached by working first on their basic components, above all the transistors. Figure 4, which appeared in the original micropower handbook, foreshadowed the drop in power consumption that might be achieved in advanced transistors. These early results were obtained only at very low fre-

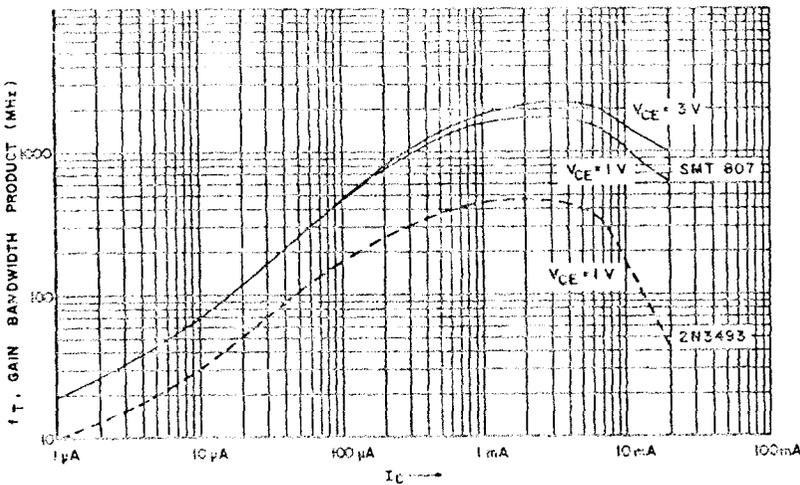


Figure 5. Performance of micropower transistor at 100 microamperes equals that of commercial counterpart at 2 millamps.

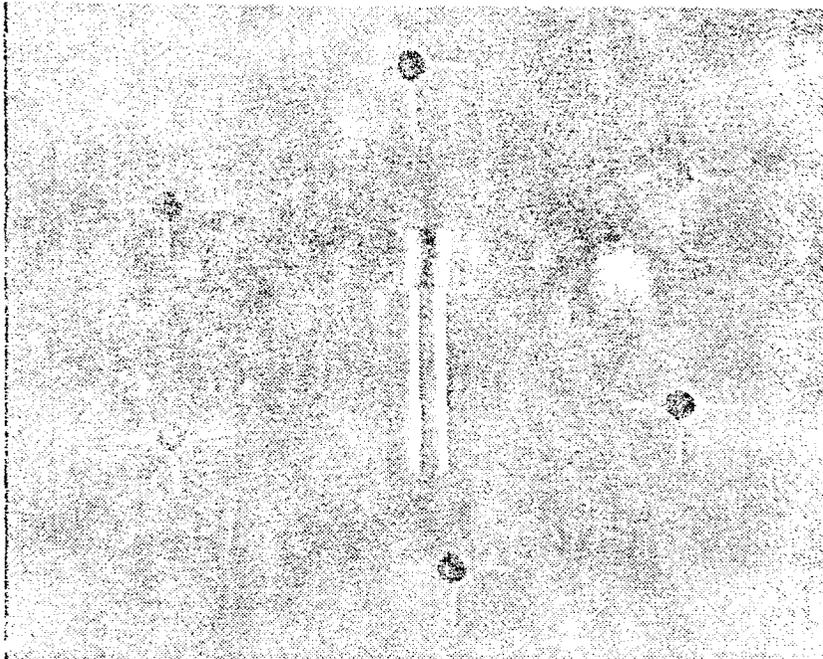


Figure 6. Micro-T packages compared with TO-18 can.

	DISPLACEMENT VOLUME (cu. in.)		PLAN AREA (sq. in.)	
	Excluding leads	Including leads	Excluding leads	Including leads
Micro-T Package00030	.00033	.0057	.0107
TO-18 package0058	.0063	.044	.044
Ratio: TO-18 to Micro-T	19:1	19:1	8:1	4:1

quency, but constant development efforts over the past two years have now produced a high-performance high-frequency micropower transistor. Figure 5 shows its gain-bandwidth product—a measure of performance—versus bias current (a function of power) compared with that of a commercially available counterpart. The special micropower devices are already available in quantity to the intelligence community.

The reduction in operating power and increase in frequency brought a further reduction in size. Figure 6 shows a half dozen of the Micro-T packages surrounding a TO-18 can. The reduction in size and power is not limited to a particular type of transistor but applies

in general to an entire family. Four complementary devices suitable for both digital and analog applications are presently available.

Micro Circuits

Transistors, though the key active elements, are not the whole story, and progress with them led to further, and continuing, developmental work in circuit design and fabrication. Circuits of progressively increasing complexity were chosen to challenge the developing technology. Results in this area have also been quite dramatic.

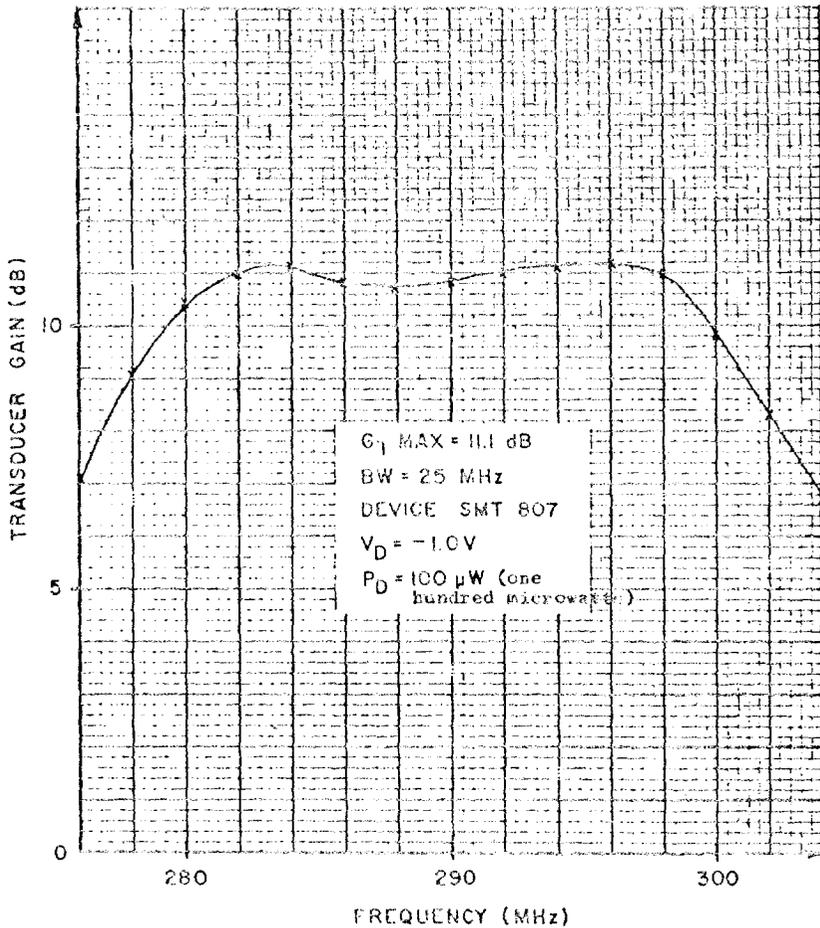


Figure 7. Performance of micropower RF amplifier.

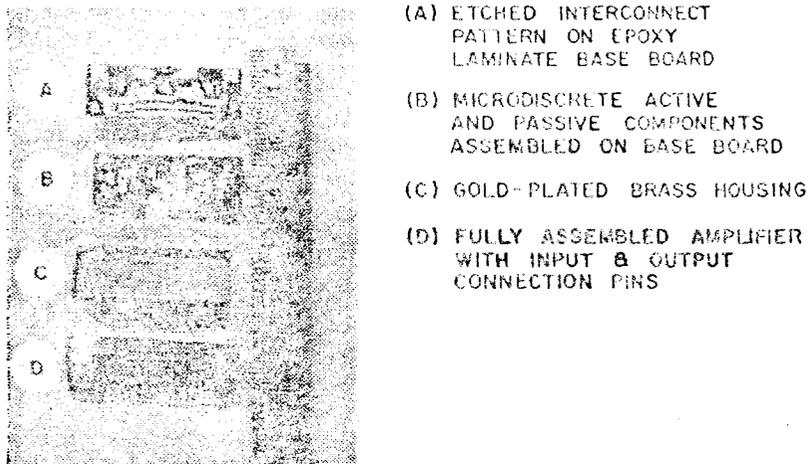


Figure 8. Three-stage wide-band micropower IF amplifier (150 MHz).

During the first year the efforts of the program were devoted to designing and fabricating two representative circuits, a radio-frequency amplifier and a digital logic function. In the amplifier a reduction in power drain of two orders of magnitude as compared to the best available commercial circuit was achieved, and size was also reduced by a factor of 100. The curve in Figure 7 shows its gain of 11 decibels, almost flat over 16 megahertz (thousand kilocycles per second), with a power input of 100 microwatts.

An equally impressive improvement was made in the digital circuit, whose power drain was reduced by a factor of 1000. Thus after a year's effort the power reduction achieved was at least 100-fold while other parameters of both circuits were maintained at the original level or improved. These accomplishments rested on careful and clever circuit design and utilization of the new micropower transistor family. The prospect of further advances along these lines continued to be extremely good when the first year's program was assessed at its conclusion.

The next logical step was to push on to more complicated circuits and subsystems, and the results were again highly favorable. The goals were accordingly expanded to include all the basic building blocks of radio receivers and transmitters. Figure 8 shows the fabrication details of a micropower intermediate-frequency amplifier, the

heart of any good superheterodyne receiver. The power consumption of this device is at least 100-fold, or two orders of magnitude, lower than that of any previous subsystem.

Oscillators have been built and tested. Converter circuits and transmitters have been fabricated with equal success and demonstrated capability. In short, a great reservoir of new technology has been tapped and brought to bear on the technical side of intelligence collection. At the present time there is every reason to believe that active pursuit of the basic program will continue to yield further advances.

Micropower Systems

The ultimate objective, that of creating complete micropower equipment, is really the criterion of success as far as intelligence gathering is concerned, so it is gratifying to be able to report that system development has been as successful as the work on component circuits. In a truly spectacular demonstration of what can be achieved, candle-power has been used to operate a complex repeater unit consisting of a receiver, a transmitter, digital processing circuits, and a solar cell network for energy conversion. The entire unit, literally driven by the light from a candle, continued to function perfectly in conjunction with the other units of the repeater network.



Figure 9. Micropower receiver.

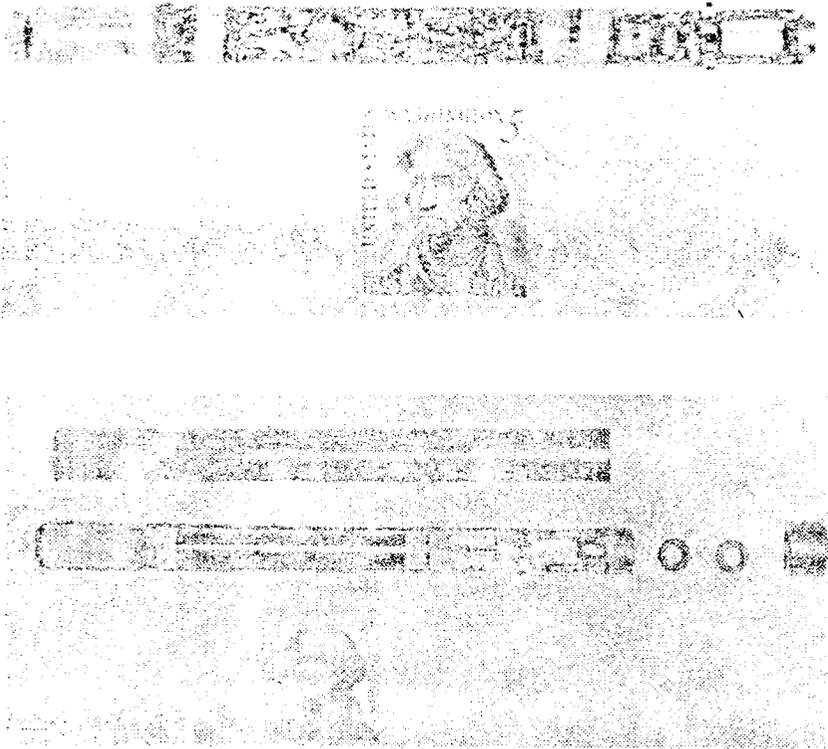


Figure 10. Micropower pencil receiver. Circuitry visible at top; assembly shown below.

The receiver in this repeater is shown in Figure 9. Its performance is comparable to that of a standard communications receiver, normally about 12" x 12" x 3". At a center frequency of 300 MHz it has a noise figure of 2.6 decibels in a bandwidth of 15 MHz—a figure not so unusual except that only one thousandth of a watt is required to operate it.

The impact of the availability of this type of electronic equipment is very significant. The operation of a repeater from a candle, of receivers such as the above from single batteries, and almost as many other marvels as one cares to dream about are at hand. The actual application of these possibilities is not so straightforward as it may at first seem; we have not discussed the mechanical problems associated with microtechnology. But these problems, though many and complex, are certainly not unsolvable. That solutions are possible is

perhaps best illustrated in Figure 10, showing a full superheterodyne receiver, including antenna, audio section, and battery, inside a pencil. The system runs on two hearing-aid batteries and performs as well as any conventional portable.

Some Future Goals

With systems like those described above available, the intelligence community can begin to approach operational problems from an entirely different point of view. Problems that were impossible just a few years ago have become solvable through micropower techniques. When a communications-quality receiver considerably smaller than a package of cigarettes can be operated from the light of a candle, battery life and resupply no longer trouble an agent in hostile territory. The problems are not radically different, but the range of possible solutions has been tremendously broadened.

The scope of this technology can be illustrated by a few advanced concepts as listed below. These are at present either undergoing development or being conceptually explored.

High-density digital storage: The fabrication of a microminiature unit capable of storing 200,000 bits of digital information in a cubic inch. This unit, operating on a 10-milliwatt total power drain, will make on-site processing or storage a reasonable design requirement in future intelligence collection systems.

A 50- to 10,000 megahertz surveillance receiver in a five-pound microminiature package. Putting into five pounds what ordinarily requires a full rack of equipment has enormous implications for the size and range of the reconnaissance vehicle.

Distributed jammers. Considering the high efficiency of the micropower transmitters, it is reasonable to consider deploying vast arrays of low-power oscillators in the area of any potential electromagnetic intruder. An orbital vehicle would be particularly susceptible to such jammers since they could be put into orbit too and powered by the sun.

A 6-bit analog-to-digital converter powered by one penlight cell and one cell $\frac{5}{8}$ " in diameter by $\frac{1}{32}$ " long. The life expectancy of the batteries would be ten years.

The remarkable nature of such developments leads one to speculate whether they are about to reach a fundamental limit that nature has surely set. Many people like to draw comparisons between the human brain and the electronic computer. If we adopt, therefore, the brain

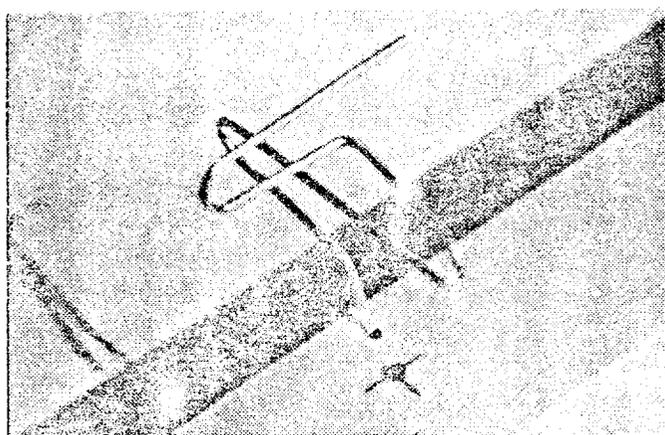


Figure 11. Two transistors.

as our standard, we can measure how close we are to this standard with micropower circuits.

A logic element, the basic building block of the computer, compares with the brain's neuron on a one-to-one functional basis. The neuron is a hundred times smaller than any micropower circuit, though also 100,000 times slower in operating. The real surprise comes, however, in power consumption: a neuron operates at about one tenth of a nanowatt, 10,000 times less power than the best micropower circuit made to date. It is therefore apparent that much remains to be done in the future before we achieve the goal nature has set up for us. We have been working only three years, to be sure, and Mother Nature a billion.

The Latest in Transistor Fabrication

Finally, let us examine the results of work done under recent contracts involving even more advanced concepts. One aspect of this work is the use of a highly sophisticated optical projection masking system for depositing accurately the elements of a minute transistor. This equipment will constitute the means for fabrication of the next generation of micropower transistors. Reducing the size of a given transistor by one half, if all other parameters remain proportionately the same, reduces its power consumption by one half; but this reduction in size automatically doubles the requirement for precision in the fabrication.

First let us compare the micropower transistors currently in production with previous devices. The original Shockley alloy transistor made in Bell Laboratories 18 years ago is shown in Figure 11 above one of the current series.

A fairer comparison can be drawn between the current micropower transistor and its best previous counterpart. Figure 12 is a photomicrograph of one of the best high-frequency, low-power transistors available in 1965. The important feature is the narrow finger-like stripes 0.2 mil (5 microns) in width. It should be observed that some of the fingers are of slightly different widths and do not always fall directly in the center of the window space provided for them. The difficulties experienced in trying to achieve uniformity and precision are evident.

In the photomicrograph in Figure 13, one of our current micropower devices, the finger-like stripes are 3 microns in width, reduced by al-