Solid-State Microwave and Millimeter-Wave Sources Development—A Personal Account

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Abstract—**The personal experience with the development of solid-state microwave and millimeter-wave sources in the late 1960's and early 1970's is described.**

I. INTRODUCTION

ONE OF THE PRIMARY requirements in developing a microwave system is a microwave power source. Solid-state microwave and millimeter-wave sources, in particular, have played key roles in the history of the development of many modern systems such as communications, radars, satellites, seekers, and guidance systems. The history of solid-state microwave devices now spans over half of the 100-year history of IEEE, when we consider the development of solid-state theories, crystal detectors, and superhetrodyne techniques. It is interesting to note that even the FET device, which is currently one of the most active areas of solid-state microwave devices developments, can trace its origin back to the early 1930's. The principle of the FET was originally demonstrated in the early 1930's by Julius Lilienfield and Heil using the surface field effect to achieve a solid-state amplifier. Bipolar transistors are over 30 years old, and the two-terminal negative resistance devices such as tunnel diodes, IMPATT, Gunn devices have now all reached adulthood, over 21 years old, and matured as practical devices used in many systems. Considering such a long history, it would be impossible for me to cover the history of solid-state microwave sources comprehensively. Thus, I choose to share my own personal encounter with the development of solid-state microwave devices technology which I took part in as a young microwave engineer during the period of the late 1960's and early 1970's.

II. SOLID-STATE PLASMA

My first encounter with solid-state microwave devices was as a graduate student at the University of California, Los Angeles. My research topic was to investigate millimeter-wave propagation through solid-state plasmas in semiconductor crystals under a magnetic field. Under an externally applied magnetic field, the conductivity of a solid-state plasma becomes a tensor quantity, i.e.,

$$\bar{\bar{\sigma}} = \begin{bmatrix} \alpha_\perp, & -\alpha_\times, & 0 \\ \alpha_\times, & \alpha_\perp, & 0 \\ 0, & 0, & \alpha_\parallel \end{bmatrix}$$

where subscripts $\parallel$, $\perp$, and $\times$ refer to the directions parallel, perpendicular, and off-diagonal elements of the tensor with respect to the applied magnetic field B_0. An electromagnetic wave traveling along the direction of the applied magnetic field in such an unisotropic medium will have propagation constants

$$K_\pm = \sqrt{\omega^2\mu_0\epsilon \pm \omega\mu_0\alpha_\times - \omega\mu_0\alpha_\perp}$$

where subscripts + and − refer, respectively, to the left-hand and right-hand circularly polarized waves, which propagate at different phase velocities in the medium. This is the cause of the Faraday rotation a plane wave experiences through the unisotropic medium. From the published literature, I learned that the amount of the Faraday rotation is directly proportional to the strength of the applied magnetic field, i.e., $\theta/l = VB_0$, where V is called the Verdet constant.

The experiment was on an n-type indium-antinusnide crystal cooled to the liquid nitrogen temperature. As the first step, I designed and started constructing an experimental setup. I quickly learned that, to be a microwave engineer, one must be a good mechanical, package, vacuum, and thermal designer. My earlier training in mechanical design, machining with lathes and milling machines, and thermal analysis techniques became helpful. However, welding stainless-steel sheet metals to construct a container with vacuum jacket for liquid nitrogen and the experimental setup was not very successful. So, knowing that a styrofoam coffee cup held hot coffee very well, I constructed a container with styrofoam, instead. It worked well, though it did not look as good as the stainless-steel container would have. With this, I started the long awaited experiments. I detected the Faraday rotation. However, contrary to my expectations, the amount of the rotation decreased with increasing magnetic field (Fig. 1). I was puzzled and went through the equations. I found the reason. The Faraday rotation is a linear function of the applied magnetic field in the region where the Hall angle is small, i.e., $\mu_e B_0 < 1$ where μ_e is the electron mobility in the solid, while my experiment is in the region where the Hall angle is relatively large, i.e., $\mu_e B_0 > 1$. Under a large Hall angle condition, the propagation constant is approximated by

$$K_\pm^2 \sim \pm\omega\mu_0\alpha_\times.$$

Thus, it was normally considered that only one type of circularly polarized wave, viz, helicon wave, can propagate

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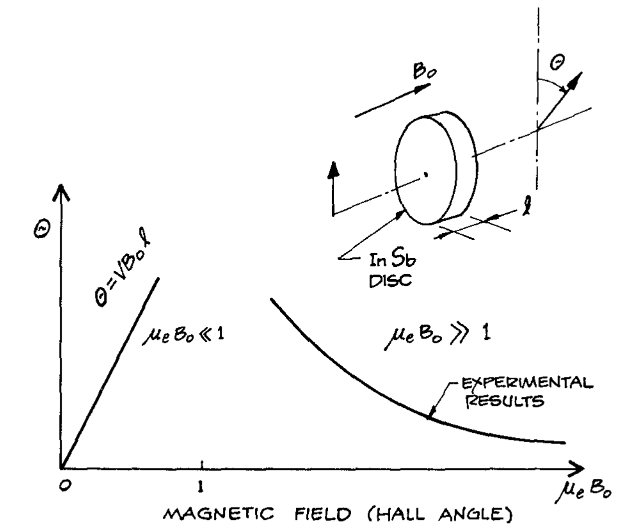

Fig. 1. Microwave Faraday rotation through a solid-state plasma.

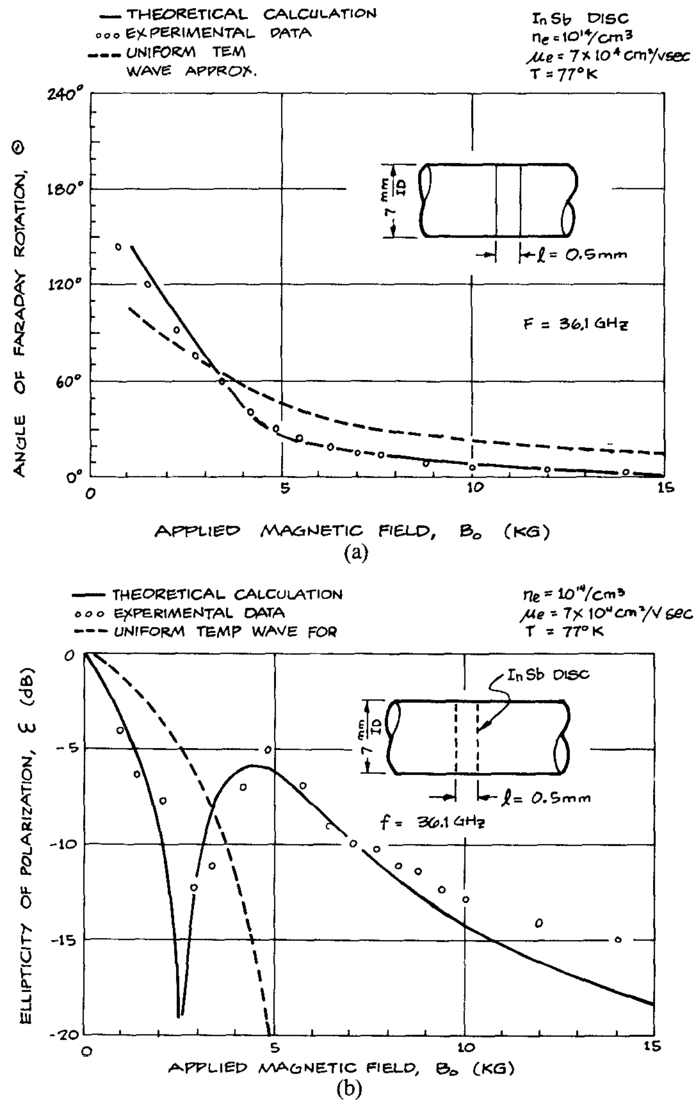

Fig. 2. Comparison of theoretical calculation and experimental results of microwave Faraday rotation through a solid-state plasma.

and the other circularly polarized wave cannot, in a solid-state plasma under a strong magnetic field. Therefore, we should not expect to observe Faraday rotation, i.e., a linearly polarized wave should be converted into a circularly polarized wave by a solid-state plasma under a strong magnetic field. But I did observe the Faraday rotation.

Detailed examination of the wave equation revealed that the helicon wave approximation assumes high conductivity and neglects displacement current. However, the semiconductor sample I was experimenting with had a relatively high resistivity so that displacement current could not be ignored, i.e.,

$$\omega^2 \mu_0 \epsilon > \omega \mu_0 \alpha_\times \gg \omega \mu_0 \alpha_\perp .$$

Under this condition, both the left- and right-hand circular polarized waves can propagate with very small loss through the plasma, and we should be able to observe a Faraday rotation. Encouraged by this finding, I started calculating the amount of the expected Faraday rotation as a function of the applied magnetic field. Sure enough, the amount of rotation decreases with the increasing magnetic field. However, a detailed check between the experimental data and calculation showed a significant amount of difference. This was more or less expected from the fact that the calculation was based on the plane TEM wave assumption while the experiment was with a circular waveguide. So I worked out Bessel's equations.

The recalculated values based on the circular waveguide analysis showed general agreement with the experiment. However, the experiment showed a sharp resonance, particularly pronounced in the resulting ellipticity (Fig. 2). I was puzzled. Then it occurred to me to realize that the crystal sample does have a finite thickness. Thus, we have impedance mismatch and reflections at the surface. So I included the multireflection into the analysis. To my delight, the new calculations showed very good agreement with the experiments, including the fine structure arising from the multireflection.

From this process, I learned that an analysis is as good as the model used. This was a very valuable experience that helped me in many situations later.

Being a microwave engineer armed with the results of the investigation, I designed and developed nonreciprocal devices, viz., isolators and circulators. It was a challenge to meet practical problems such as minimizing insertion loss, maximizing isolation, and obtaining good input/output matching. It was a satisfying feeling, moreover, to have developed a device and seen it working.

III. IMPATT Amplifiers

Later in the early 1970's at Hughes, I was engaged as team leader in the development of millimeter-wave IMPATT amplifiers. By this time, theories of the device operation had been well developed by many researchers. To understand the physical principle of the IMPATT device operation, my experience with the solid-state plasma became handy. The dynamics of the electrons and holes in the diode are governed by the same set of equations as those used for the solid-state plasma. The requirement was

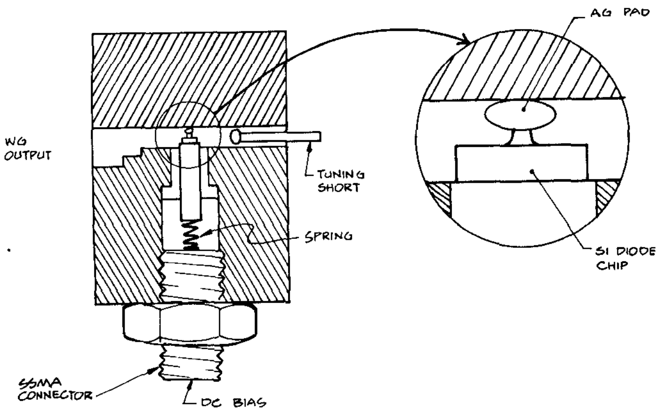

Fig. 3. Mesa diode mounted in a waveguide circuit.

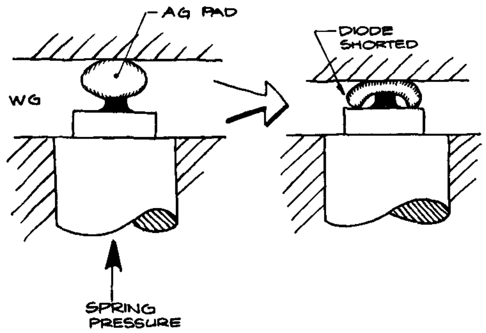

Fig. 4. Mesa diode penetrates through silver pad.

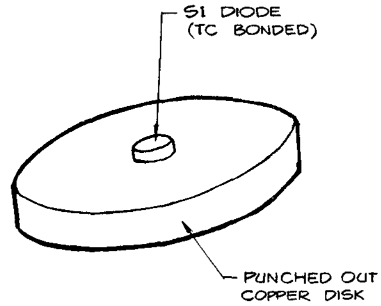

Fig. 5. Silicon diode thermal compression bonded onto copper heat sink.

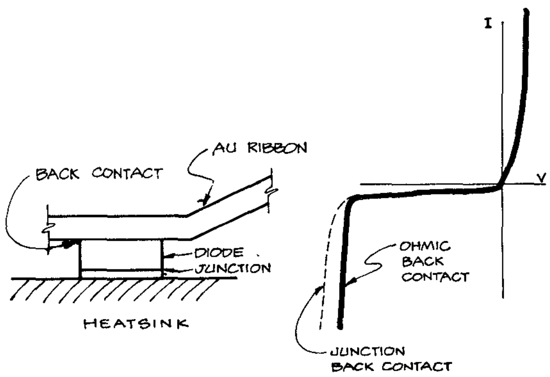

Fig. 6. Effect of nonohmic back contact.

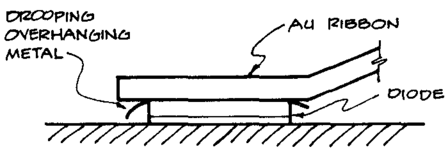

Fig. 7. Drooping overhanging metallization shorts out diode.

to achieve 100 mw of power output. Calculations showed no difficulty in achieving this power level. First, we had to make diodes. So we came up with a diode design and started fabricating them.

We started fabricating diodes with a mesa structure. Thermal analysis indicated that we must provide a good heat sink close to the junction. We were also concerned about the adverse effect of parasitic inductance at 60 GHz. So we devised a mounting scheme for the diode with a silver pad as shown in Fig. 3. The amount of pressure applied to the diode was critical; too little would result in high thermal resistance and too much would short out the diode. After a systematic study, we empirically arrived at a proper amount of pressure. However, we found that all the diodes eventually would end up shorted. This was due to the fact that a typical diode of 0.001-in-diam junction, which is approximately 1/10 of a human hair's diameter, acted like a tip of a sharp needle and penetrates through the silver as shown in Fig. 4. So we had to devise a better way of mounting a diode.

We developed a technique to thin a silicon wafer of 1″ diam down to 0.0005-in thickness and still be able to process it. This is like holding a thin paper sheet on an edge and writing on it. After a great deal of effort, we managed to thermal compression bond the diode to the copper disk with the junction close to the heat sink. A gold ribbon was then connected to the other side. This was accomplished by bonding a 1-in-diam $\times$ 0.001-in thin silicon onto a copper disk with a press, then etching off most of the silicon material other than the diode area. The individual diodes on a copper heat-sink disc were then punched out. The diode density was relatively low ($\sim 100/\text{in}^2$) in this process. However, this improved the situation considerably.

There were other problems in diode fabrication processes. For example, many diodes failed on the substrate side. Careful examination of the $I-V$ characteristics revealed that the metal contact to the substrate was a junction rather than an ohmic contact as depicted in Fig. 6. This resulted in heat generation relatively far away from the heat sink, leading to diode failure. So we had to change the arsenic-doped silicon substrate material to low resistivity to achieve good ohmic contact. Another problem was an overhanging metalization resulting from trim etching that would droop down and short out the diode after several hours of operation as shown in Fig. 7. This had to be corrected by changing the fabrication process.

For the system application, packaged diodes are desirable. So we designed a special package with small parasitics for the 60-GHz diode. Designing the package is much easier than fabricating and assembling it. It took us considerable time and effort and design iterations to develop fabrication and assembly techniques for the millimeter-wave diode packages.

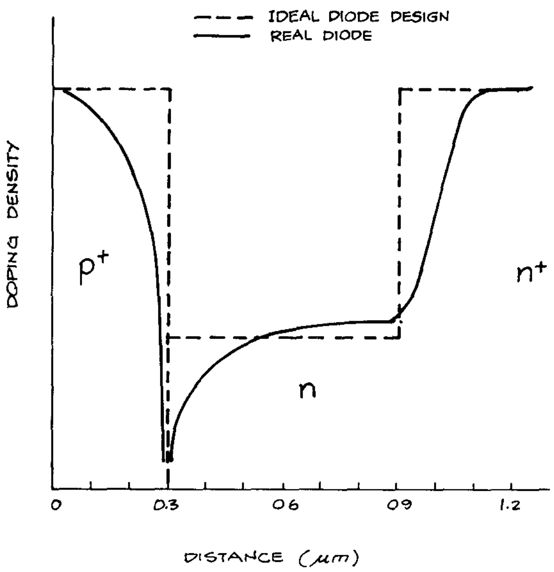

Fig. 8. Ideal and real diode material doping density profiles.

On the RF front, we struggled to achieve the output power of 100 mW. The diode performance is critically dependent on the doping profile of the expitaxial material. The desired active layer thickness for the 60-GHz diode is 0.6 μm. The diode design assumes an ideal uniform doping density with abrupt transitions. In a real diode, however, we do have finite transition lengths and, quite often, nonuniform doping density as illustrated in Fig. 8. To compound the problem, control and measurement accuracies of the doping density profile were limited to 10–20 percent, so we had to accept the low yield. We started the project with monthly review meetings. The frequency of the review meetings soon increased to every other week, then to every week, and finally to twice a week in our effort to find the way to achieve the program objectives. We generated action items one after another in pursuit of the goal. Finally one day, we saw the power-meter needle go up to the 150-mW level. We first doubted our eyes. After re-examining the calibration of the setup, we knew that the power was real. We quickly tested a number of diodes from the same production lot and happily found that many diodes produced more than 100-mW power output. Our spirits went up by many decibels, and we called up the program manager to let him know.

The next step was to make amplifiers. We quickly learned that achieving an output power level from an oscillator is one thing, but stabilizing the oscillation to achieve amplifications is another. To start with, we could not characterize the RF properties of the diodes in this frequency range. There was no network analyzer available, not even a slotted line. What we had were very basic test instruments such as frequency meters, attenuators, directional couplers, detectors, bolometers. Even those available were very difficult to procure, were fragile and expensive, and had a long delivery time. We had to learn to make many test components ourselves. For example, we built a sweep generator with an IMPATT diode, a video detector with a Schottky-barrier mixer diode, Faraday rotation isolators, and junc-

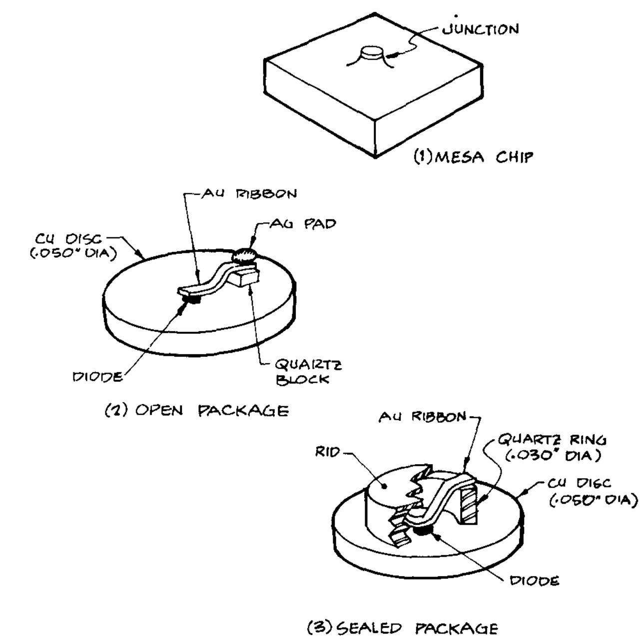

Fig. 9. Evolution of millimeter-wave IMPATT diode packages.

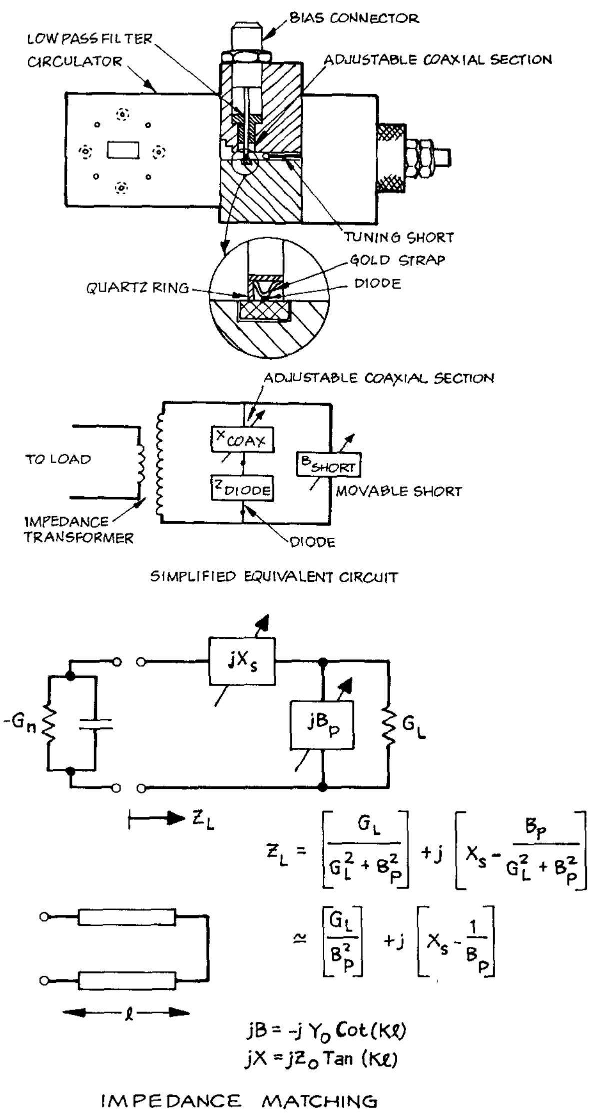

Fig. 10. Millimeter-wave IMPATT amplifier circuit.

tion circulators. Later we made these as products and started to market them. The product line has since grown to be a sizeable business. With these limitations, we had difficulties stabilizing the oscillation. Our circuit was basically a reduced-height waveguide circuit with a sliding tuner. In this circuit, the diodes either oscillated or did not amplify at all, no matter what we did to provide a low impedance to stabilize the oscillator. We then came to realize that, in order to provide proper impedance matching between the device and the load, both real and imaginary parts of the impedance must be matched, and that to accomplish this, two degrees of tuning freedom must be provided in the circuit. So we came up with a circuit design that provided two tuning elements: a coaxial tuning section connected in series with the diode and a sliding tuning element connected in parallel with the load as shown in Fig. 9. With this new circuit, we made a significant advancement toward achieving the goal. Not only did we successfully build amplifiers with 100-mW output power, but we also extended the output power level to greater than 250 mW. Then, by combining amplifiers with hybrid couplers, we achieved 500 mW with a two-amplifier combiner and eventually 1 W with a four-amplifier combiner. In parallel with achieving RF performance goals, we established reliability and producibility for the devices. The development of the device was then extended to other frequency ranges such as 90–100 GHz and 140 GHz, and to high power double-drift IMPATT diodes.

IV. Conclusion

I am certain that my contemporaries in the solid-state microwave/millimeter-wave sources field shared my experience through similar passages. These early experiences told us that seemingly minor, tedious, sometimes frustrating problems blocking our passage must be removed first to achieve important program goals. To solve microwave problems, we often have to solve problems in semiconductor processing, machining techniques, and packaging designs. A student taking a microwave course finds problems given at the end of each chapter. In a real situation, however, he must first find and define the problems, then proceed to figure out solutions.

The development of solid-state devices for microwave and millimeter-wave applications are currently going stronger than ever. Millimeter-wave IMPATT devices are now being used to build combiners for transmitter applications. Double-drift IMPATT diodes yield greater than 1 W per device. Comprehensive lists of millimeter and microwave test equipment and components are currently available. FET devices are pushing the frequency coverage into the millimeter-wave range. Microwave and millimeter-wave power sources can now be made in monolithic IC forms. The need for solid-state T/R modules for phased-array radars with active apertures are now a reality. Use of millimeter-wave frequencies for communications, radars, and weapon guidances are also here. It is important to keep in mind that implementation of these systems will largely depend on the successful development and low-cost production of the necessary solid-state sources. In addition to system applications, I can see that there are new types of solid-state microwave sources over the horizon yet to be invented and developed. While celebrating and looking back on the century-old history of IEEE, it is certainly interesting and exciting to speculate the seemingly limitless horizon of the development and application of solid-state microwave devices for the rest of this century and beyond.

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Professors W. D. Hershberger and R. S. Elliott introduced me and my classmates at UCLA to the microwave field. With their encouragement, we launched our microwave careers. I would like to acknowledge my colleagues at Hughes with whom I shared my early experience in developing solid-state microwave and millimeter-wave devices: in particular, N. B. Kramer, T. A. Midford, F. J. Bernues, R. S. Ying, E. Nakaji, D. L. English, and M. M. Morishita. We have been working together on developing and advancing the technology for over 10 years now.

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