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HIGH EFFICIENCY IMPATT DIODES FOR 60 GHz INTERSATELLITE LINK APPLICATIONS

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SUMMARY

Intersatellite links are expected to play an increasingly important role in future satellite systems. Improved components are required to properly utilize the wide bandwidth allocated for intersatellite link applications around 60 GHz. IMPATT diodes offer the highest potential performance as solid-state power sources for a 60 GHz transmitter. Presently available devices do not have the desired power and efficiency. High efficiency, high power IMPATT diodes for intersatellite link applications are being developed by NASA and other government agencies. This paper describes the development of high efficiency 60 GHz IMPATT diodes by NASA. These programs are cofunded by the U.S. Air Force, Space Division.

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INTRODUCTION

As satellite systems grow in capacity and complexity, intersatellite communication links are expected to play an increasingly significant role. The NASA Tracking and Data Relay Satellite System (TDRSS) has S-band and Ku-band intersatellite links with low earth orbiting spacecraft as part of its operational capability. Future NASA, military, and commercial spacecraft will require high data rate systems. Nearly 10 GHz of bandwidth is presently allocated around 60 GHz (V-band) for intersatellite link applications. In order to effectively utilize this resource, electronic components must be developed for integration into systems. This paper addresses the development of one of those components, namely, an efficient solid-state source of rf power at 60 GHz.

Of the presently known solid-state devices, the IMPATT diode is the leader in both theoretical and achieved power from 10 to 300 GHz. The output power varies as $1/f$ at lower frequencies due to thermal limitations and then drops off as $1/f^2$ or faster at mm-wave frequencies. This may be seen in figure 1 where recent results of Si and GaAs devices are compared (ref. 1). It is seen that GaAs has a performance advantage in both power and efficiency below 50 GHz with Si having a large advantage at 94 GHz and above. The nature of the degradation observed in GaAs at higher frequencies is uncertain and is presently under debate. However, very recent work at 60 GHz has decreased the performance difference and indicates that GaAs is likely to have higher power and efficiency than Si, notwithstanding ongoing work in Si technology. Work at 94 GHz should also be very interesting with regard to the status of mm-wave performance of GaAs.

NASA Lewis is currently sponsoring two development contracts for a one watt, 15 percent efficient, high reliability 60 GHz IMPATT diode as shown in table 1. The contractors are Hughes Aircraft Company, Electron Dynamics

Division, Torrance, California, and M/A-COM, Gallium Arsenide Products Inc., Burlington, Massachusetts. Each contractor has chosen GaAs as the active material and is utilizing large signal (nonlinear) computer design techniques. For material growth, Hughes is using Molecular Beam Epitaxy (MBE) whereas M/A-COM is using Organo-Metallic Chemical Vapor Deposition (MOCVD). These advanced material growth techniques are necessary due to the high frequency and high performance goals of the program. Each contractor is utilizing diamond heat sink (DHS) technology due to stringent thermal requirements. After a brief review of IMPATT operation, the current status of these programs will be discussed in detail.

60 GHz IMPATT OVERVIEW

IMPATT oscillations were first discovered in 1965. The field is mature and also very active (ref. 2). Present work is largely involved with improvements in performance through refinements in design, material growth, and processing. The physical picture of the rf power generation is straightforward. A pn junction diode is reverse biased near breakdown. An rf voltage is applied to the diode. During the half cycle when the rf voltage adds to the dc voltage, electron-hole pairs are created by avalanche impact ionization in the avalanche region around the junction. Due to the mechanics of this generation process, the maximum charge pulse occurs when the rf voltage has decreased to zero. This introduces a 90° phase delay between the rf voltage and the pulse of charge. The charge pulses then drift toward the diode contact areas. The electrons drift in the n region and the holes in the p region, inducing an external current. During this portion of the rf cycle, the rf voltage has the opposite sense to the dc voltage. If the diode is designed so that the time of transit of the charge pulses is equal to one-half of the rf cycle, an additional 90° phase delay is introduced. The situation is that there is nearly zero current during the positive half of the rf cycle and positive carrier flow against a negative rf voltage in the second half of the cycle, thus generating rf power. For high efficiency and high power, one needs to generate as large a charge pulse as possible while maintaining the proper phase relations between current and voltage and also achieving the necessary impedance and thermal values.

An example of a 60 GHz GaAs IMPATT diode design will be given. This design was generated and analyzed by Mains and Haddad (ref. 3) of the University of Michigan through the use of their large signal (nonlinear) computer simulation program. The doping profile is shown in figure 2 and the physical and operating characteristics are listed in table 2. The profile shown is a hybrid double-drift profile which means that both the p and n material have drift regions and that the n material also has a higher doped region at the pn junction to confine the avalanche. There are several features to be noted. The doping profile requires several sharp changes in a distance of less than 1 μm. Nonabrupt doping changes and nonuniform doping within layers are known to degrade efficiency. Thus, stringent requirements are placed on the material growth process. The physical size of the diode is small and the current density is large. This places demands on the entire processing and fabrication sequence. The thermal resistance is calculated assuming that a diamond heat sink is used, that there is a minimum of material between the junction and the heat sink, and that there is no extra thermal resistance from poor processing. This means that a reliable diamond heat sink technology is necessary. Finally, the negative resistance of 1 ohm and capacitive reactance

of 11 ohms are about the minimum values which may be matched into rf circuitry. This design was based on the drift-diffusion model of carrier transport in a semiconductor. Using a more realistic energy and momentum relaxation model, relaxation effects which occur on the picosecond time scale may be important and may change the design features to some degree (ref. 4).

HUGHES APPROACH

In order to achieve the goals listed in table 1, Hughes has chosen GaAs using MBE as their primary material growth approach with conventional Vapor Phase Epitaxy (VPE) as a backup. The high frequency and high power goals require several sharp doping changes in a distance less than 1 μm. The high efficiency goal requires that these doping changes be sharp and that doping within each region be very uniform. From an analysis of large signal computer simulations, Hughes has chosen the double-drift hybrid profile. A recent Secondary Ion Mass Spectroscopy (SIMS) analysis of this profile which was grown using MBE by Perkin-Elmer Corp. is shown in figure 3. The sharp transitions and excellent uniformity within the layers may be seen. The transitions from one doping level to another take place in approximately 200 Å distance and this should be sufficient for this program. A portion of this apparent transition width is due to instrumental rounding in the SIMS analysis. Double-drift flat profiles have also been grown but have not performed as well. Single-drift profiles using Schottky contacts were grown early in the program but suffered from large leakage and burn out at low bias. MBE material is also being grown for Hughes at Cornell University. Installation of a MBE machine at Hughes has recently been completed and IMPATT material growth will begin soon. VPE growth has also been done but has not been as successful. Future plans are to concentrate exclusively on MBE growth.

Although the initial diode design was performed using small signal analysis, Hughes has worked with UCLA and has set up their own program for large signal computer analysis. This analysis is essential for high performance due to the nonlinear nature of IMPATT operation. There are still questions to be answered regarding the modelling of parameters which are critical to IMPATT operation. The most important of these are; the ionization rate versus electric field, saturation velocity versus temperature, and diffusion constant versus electric field. Recent large signal results show excellent agreement with experiment in power and efficiency.

Processing of the diodes is a key step in the fabrication sequence. It was predicted and experimentally verified that plated heat sink diodes would not provide adequate heat removal from the junction. Hughes has developed a pill diode process for thinning and metallizing the diodes for mounting on a diamond heat sink. The pill process has an extra advantage in that the number of diodes is increased by a factor of 5 over that from plated heat sink processing. This is especially important due to the small area wafers which are often necessary in MBE machines. During the process, the p metallization (Au/Zn) is done followed by wafer thinning from 250 to 10 μm. The n metallization (Au/Ge/Ni) is evaporated and alloyed, different size dots are defined on p and n sides and the thinned wafer is etched through to form the pill diodes. The metallization in this process is critical in that the p metallization must be able to bond well to the metallized diamond without excessive pressure or temperature. This process cured problems associated

with excessive bonding pressures which often lead to cracking of the GaAs diode. A metallized diamond is hot pressed into a copper stud and the pill diode is thermo-compression bonded to the diamond. These two steps determine the thermal characteristics of the device and the quality and reproducibility must be high. A metallized quartz ring and preformed ribbon are used to make electrical connection and also to control the magnitude of the parasitic capacitance and inductance. Finally, the diode is tested in a coaxially-coupled reduced height waveguide cavity. This cavity was chosen for its flexibility in changing dimensions and impedances and also the ease with which devices may be inserted and removed without disturbing the circuit.

Although hampered somewhat by a lack of material, good progress is being made. The material problem was due to older MBE machines with very limited growth area per run, ~1.5 cm^2, and the fact that the difficult doping profile was not easily achieved. New generation MBE machines which now have excellent uniformity over a 2 in. wafer and also allow for multiple runs with one loading will alleviate the first problem. Operator experience and increased capability of the machines will make the realization of a particular profile easier to accomplish. Best results to date have been 1.0 W with 13 percent efficiency at 56 GHz. The noise characteristics will be measured later in the program. Thermal resistance values are about 50° C/W and will have to improve in order to achieve the desired performance.

M/A-COM APPROACH

For their development of a 60 GHz IMPATT, M/A-COM has chosen GaAs with a double-drift hybrid Read design and diamond heat sink. The material is grown both by conventional VPE methods and also by the MOCVD technique. The doping profile has been obtained through use of the large signal program at the University of Michigan. Several options for 60 GHz operation were analyzed and a double-drift hybrid Read design was chosen. The predicted performance was 1.3 W output at 14 percent efficiency with a current density of 18 kA/cm^2 and required thermal resistance of 28° C/W as shown in table 2.

The material growth has proceeded well in both VPE and MOCVD. Diethyl zinc (DEZ) has been successfully used as a p dopant in the VPE growth with good reproducibility. Also, thin layers and sharp transitions have been successfully demonstrated. The transition sharpness has been observed to be less than 500 Å using C-V measurements but this is about the sensitivity of the C-V technique. Nevertheless, due to the rapid growth rate of the VPE technique, it is difficult to execute the many doping changes and to maintain good uniformity within layers and sharp transitions between layers.

MOCVD, on the other hand, has the potential to grow sharper profiles while maintaining good uniformity. MOCVD growth takes place in a cold wall reactor by the irreversible pyrolysis of an alkyl gallium compound and arsine. Trimethyl gallium (TMG) is the compound normally used. This pyrolysis takes place in a single hot zone which is heated by rf induction. Low substrate growth temperature, 650° C, and high gas flow rates permit rapid changes of doping level and give this process the capability of producing complex structures with sharp transitions. The entire system has been automated for reproducibility. The dopants being used are silane and dimethyl zinc (DMZ).

As a result of experiments with baffles and flow rates, uniformity of doping and thickness in the n layer is ±10 percent run to run and the n layer doping is uniform to ±10 percent across a 2" wafer. There is more uncertainty in the p layer measurements and these values may be ±20 percent. Work is continuing in that area. It is felt that the doping transitions are sharper than 200 Å although this is below the sensitivity of the C-V measurements.

The rf testing is accomplished using a "Top-Hat" circuit. This circuit was chosen for its broadband capability and for ease of interchanging diodes. Impedance matching is accomplished by a variety of top-hats with different geometries which are easily interchanged and also by interchangeable heat sinks of different sizes. This circuit has proven to be versatile in testing diodes with widely varying characteristics. Best rf results to date have been with VPE grown double-drift diodes. Highest power has been 300 mW with 11 percent efficiency at 52 GHz. MOCVD results have been less than 10 mW with low efficiency. The cause of this low output has not been determined and additional experiments are being done to determine the causes. Plated heat sinks are being used for this initial evaluation. The need for diamond heat sink to attain the 1 W level is recognized and work is in progress to develop this technology for millimeter wave devices.

RELATED 60 GHz IMPATT DIODE WORK

Due to interest in intersatellite link applications and secure terrestrial links, there are several 60 GHz IMPATT diode programs in progress. They are listed in table 3. The Hughes-NASA/GSFC program is specifically designed to improve the mature Si technology through processing, fabrication, and design optimization. The Varian-NRL program with InP has experienced problems with the p-layer and the results have been less than expected. Additional work will continue in order to explore the potential of InP for high efficiency. The remaining four programs with LeRC and AFWAL all have similar goals with GaAs but utilize different approaches. These programs ought to clearly indicate whether the knee in the curves of figure 1 is above or below 60 GHz. The trend of the results from Hughes and from Raytheon would indicate that the $1/f^2$ falloff is going to take place above 60 GHz. As part of the same program, Raytheon is also doing CW GaAs IMPATT work at 94 GHz and that data point for the GaAs-Si comparison will be significant.

The question of reliability is, of course, extremely important. Masse and Harper recently summarized the results of published reliability data on GaAs IMPATT devices (ref. 5). At a given junction temperature, say 250° C, the median times to failure varied over 5 orders of magnitude, depending on the metallization used and types of stress employed. The reliability of IMPATT devices depends basically on the operational junction temperature and the metallization system used. Reliability testing will be done at the conclusion of the NASA programs and separate reliability programs may be necessary. Most estimates indicate, however, that a 10 year lifetime in space should be achievable with junction temperatures below 250° C.

CONCLUDING REMARKS

For the NASA Tracking and Data Acquisition System (TDAS) of the early 1990's time frame, system studies indicate that V-band intersatellite links will require approximately 10 W of transmitter power. Table 4 shows recent and future 60 GHz amplifier developments. The new development will probably require 15-30 devices depending on the mode of operation chosen and the devices available. Presently available devices are in the 0.8 W range with 6-9 percent efficiency. With the higher power, higher efficiency devices under development, there will be substantial savings in amplifier complexity, weight, and prime power requirements. Weight and power may be reduced by 30-40 percent of values in table 4. This is expected to have a strong impact on the viability of the solid-state amplifier for intersatellite links.

Optical and travelling wave tube (TWT) technology offer alternatives to the solid-state amplifier described above. Work is underway in both areas. At the present time, the optical system weight is substantially higher than that required for a 60 GHz solid-state system. TWT's offer substantially more power and efficiency than solid-state amplifiers. A 75 W TWT with 40 percent efficiency is presently being developed at 60 GHz. However, at the power level of 10 W, an IMPATT based solid-state amplifier may be competitive with the TWT. Efficient devices and power combining schemes may bring the solid-state amplifier weights down to comparable TWT values. Power supplies for solid-state amplifiers are low voltage and less complex. Reliability of the IMPATTS is a key question which must be addressed.

In summary, the application of sophisticated computer design techniques, advanced material growth techniques, and careful thermal considerations are expected to lead to high efficiency high power IMPATT sources of power at 60 GHz. These devices are expected to find use for intersatellite link transmitters in the 1990's.

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TABLE I. - 60 GHz IMPATT DIODE
NASA/LEWIS RESEARCH CENTER

Goals	
Operable frequency, GHz	59-61
Output power (Oscillator), watt CW	1
Efficiency, percent	15
Reliability	Compatible with 10 year lifetime in space
Contractors	
Hughes Aircraft Co., Electron Dynamics Div., Torrance, CA	
M/A-COM Gallium Arsenide Products, Inc., Burlington, MA	

TABLE II. - 60 GHz GaAs HYBRID DOUBLE DRIFT
IMPATT DIODE CHARACTERISTICS FROM
LARGE SIGNAL COMPUTER DESIGN (REF. 3)

Parameter	Value	Parameter	Value
Diameter	2 mil	Prf	1.3 W
Area	$2.03 \times 10^{-5} cm^2$	η	14.2 percent
J_{DC}	17.7 kA/cm^2	ΔT_J	225° C
I_{DC}	359 mA	θ	[a]28.2° C/W
V_{DC}	25.5 V	G_D	(-)8.04 mS
P_{DC}	9.3 W	B_D	89.3 mS

[a]With diamond heat sink and metallization contribution of 5.0° C/W.

TABLE III. - 60 GHz IMPATT DIODE PROGRAMS

Contractor	Sponsor	Goals		Approach	Results (12/83)
Hughes	NASA/LeRC	1 W	15 percent	GaAs/MBE/DHS	1.03 W at 13 percent
M/A-COM	NASA/LeRC	1 W	15 percent	GaAs/MOCVD/DHS	0.3 W at 11 percent
Raytheon[a]	AFWAL	2 W	15 percent	GaAs/MBE/DHS	1.25 W at 11 percent
Hughes	NASA/GSFC	1.5 W	14 percent	Si/VPE/DHS	1.6 W at 10 percent
Varian	NRL	1 W	14 percent	InP/VPE	1.7 W at 4 percent (1 percent Duty cycle)
TRW[a,b]	AFWAL	2 W	15 percent	GaAs/MBE	-------------------

[a]Multiple frequency programs.
[b]Program requires substantial university participation.

TABLE IV. - 60 GHz AMPLIFIERS SPONSORED BY NASA/GSFC

Contractor	Phase I	Phase II
	Hughes,	to be determined,
	goals/results	goals
CW power out(W)	4/3.6	10
Gain (dB)	30/30	40
Bandwidth (GHz)	2.5/2.5	1
Efficiency (percent)	4/3	6
Prime power req. (W)	100/120	170
Device	10 Si IMPATTS, 7 percent efficient	---
Estimated flight Wt (kg) (with regulators)	6	13
Completion date	1983	1985

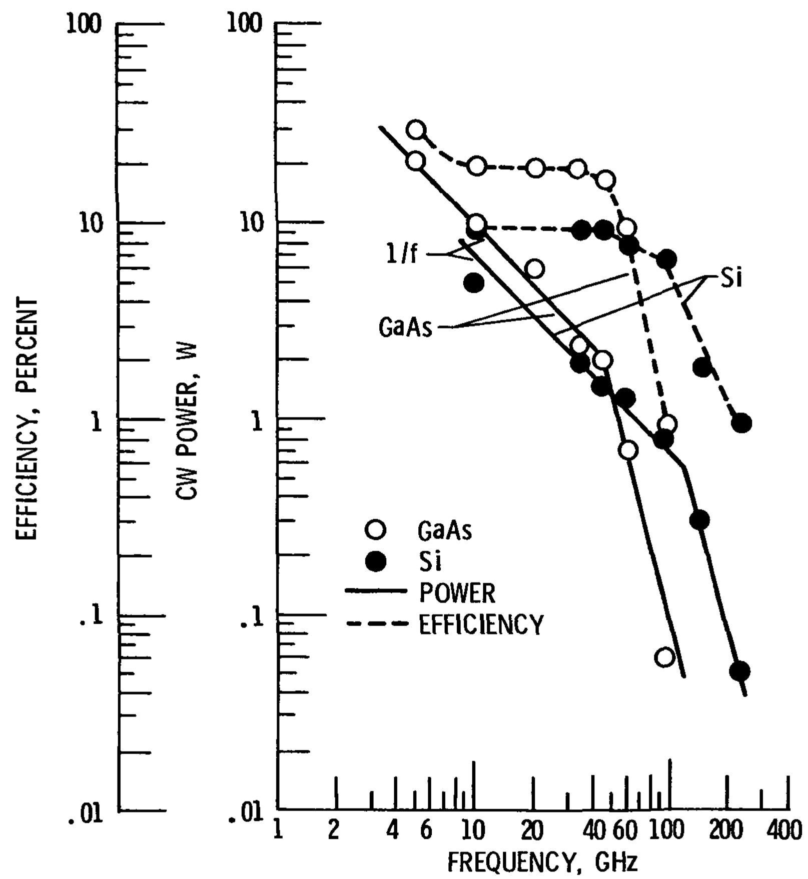

Figure 1. - Power and efficiency data for GaAs and Si IMPATT diodes (after ref. 1).

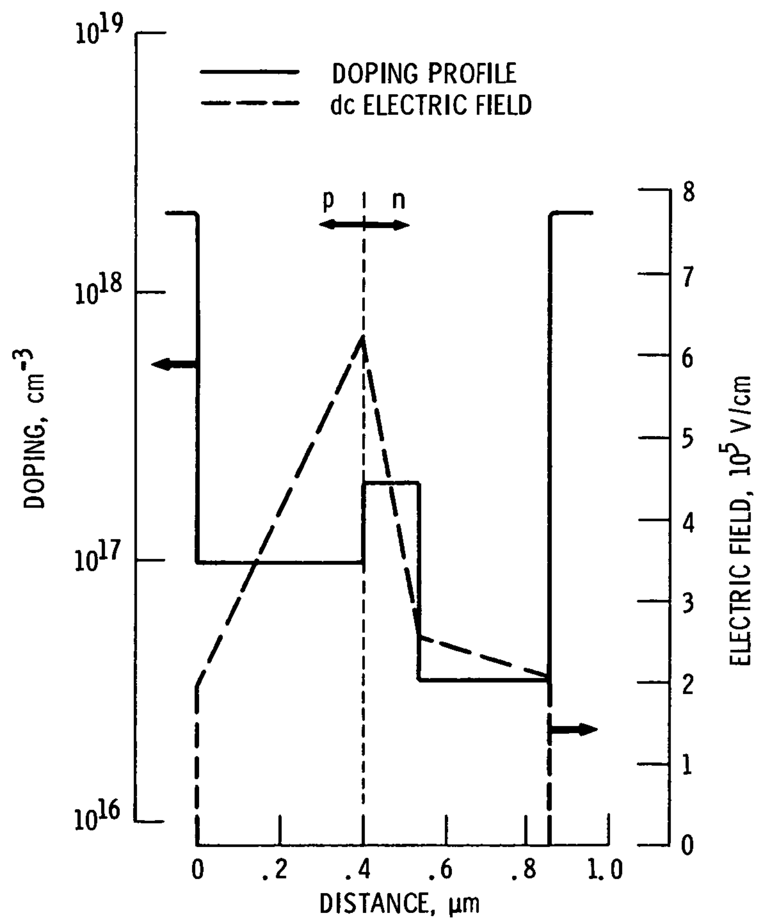

Figure 2. - 60 GHz GaAs hybrid double-drift doping profile and dc electric field at J_{DC} = 18 kA/cm^2. (After ref. 3.)

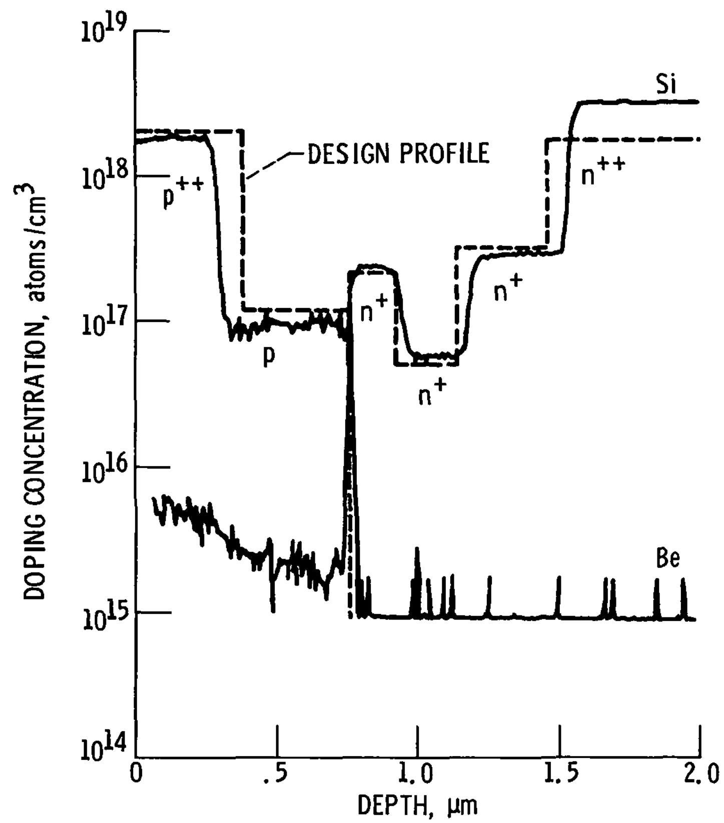

Figure 3. - Doping profile of 60 GHz IMPATT material grown by MBE and measured by SIMS compared to design profile. The p dopant is Be and the n dopant is Si.

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15 Supplementary Notes

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16. Abstract

Intersatellite links are expected to play an increasingly important role in future satellite systems. Improved components are required to properly utilize the wide bandwidth allocated for intersatellite link applications around 60 GHz. IMPATT diodes offer the highest potential performance as solid state power sources for a 60 GHz transmitter. Presently available devices do not have the desired power and efficiency. High efficiency, high power IMPATT diodes for intersatellite link applications are being developed by NASA and other government agencies. This paper describes the development of high efficiency 60 GHz IMPATT diodes by NASA.

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