

On-Wafer Measurement of a Silicon-Based CMOS VCO at 324 GHz

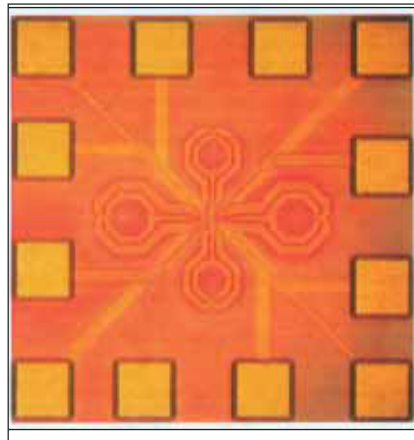
Compact, low-power, electronically tunable submillimeter-wave local oscillators are now feasible.

NASA's Jet Propulsion Laboratory, Pasadena, California

The world's first silicon-based complementary metal oxide/semiconductor (CMOS) integrated-circuit voltage-controlled oscillator (VCO) operating in a frequency range around 324 GHz has been built and tested. Concomitantly, equipment for measuring the performance of this oscillator has been built and tested. These accomplishments are intermediate steps in a continuing effort to develop low-power-consumption, low-phase-noise, electronically tunable signal generators as local oscillators for heterodyne receivers in submillimeter-wavelength (frequency > 300 GHz) scientific instruments and imaging systems. Submillimeter-wavelength imaging systems are of special interest for military and law-enforcement use because they could, potentially, be used to detect weapons hidden behind clothing and other opaque dielectric materials. In comparison with prior submillimeter-wavelength signal generators, CMOS VCOs offer significant potential advantages, including great reductions in power consumption, mass, size, and complexity. In addition, there is potential for on-chip integration of CMOS VCOs with other CMOS integrated circuitry, including phase-lock loops, analog-to-digital converters, and advanced microprocessors.

The 324-GHz CMOS VCO (see figure) was designed and fabricated according

to the design rules of 90-nm-gate-length CMOS technology. However, it was nec-



This CMOS Integrated Circuit includes a VCO that generates four signals in phase quadrature at a fundamental frequency of about 81 GHz. The four 81-GHz signals are rectified and superposed to obtain a signal at 324 GHz.

essary to follow a somewhat unconventional approach because it is impossible to make a 90-nm-gate-length CMOS circuit oscillate at a frequency greater than about 170 GHz. The essence of the approach followed here is to generate a 324-GHz signal as a fourth-harmonic signal through linear superposition of four phase-delayed, rectified 81-GHz fundamental signals: Two cross-coupled 81-GHz VCO cores generate quadrature outputs at relative phases of 0°, 90°,

180°, and 270°. These four signals are rectified by class-B amplifiers, and the outputs of the amplifiers are combined. The fundamental-to-harmonic power-conversion efficiency is significantly greater than that of traditional harmonic generation through exploitation of nonlinear circuit characteristics. Moreover, the phase noise of the output signal is less than that of traditional harmonic generation because the phase noise is limited to that of the fundamental signal.

A custom on-wafer probe was developed for measuring the performance of the 324-GHz CMOS VCO. The probe includes a unique coplanar-waveguide/coaxial-cable/waveguide transition. The probe contacts are spaced at 100 μm — a distance chosen to match the pitch of the contact pads on the CMOS VCO chip. The probe has been used to measure the phase noise, frequency of oscillation, and scattering parameters of the VCO at frequencies up to 340 GHz.

This work was done by Lorene Samoska, King Man Fung, and Todd Gaier of Caltech; Daquan Huang, Tim Larocca, and M. F. Chang of the University of California, Los Angeles; Richard Campbell of Portland State University; and Michael Andrews of Cascade Microtech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-45494

Group-III Nitride Field Emitters

Growing group-III nitride films spontaneously split into columns.

Marshall Space Flight Center, Alabama

Field-emission devices (cold cathodes) having low electron affinities can be fabricated through lattice-mismatched epitaxial growth of nitrides of elements from group III of the periodic table. Field emission of electrons from solid surfaces is typically utilized in vacuum microelectronic devices, including some display devices. The present field-emission devices and the method of fabricating them were developed to satisfy needs to reduce the cost of fabricating field emitters, make them compatible

with established techniques for deposition of and on silicon, and enable monolithic integration of field emitters with silicon-based driving circuitry.

In fabricating a device of this type, one deposits a nitride of one or more group-III elements on a substrate of (111) silicon or other suitable material. One example of a suitable deposition process is chemical vapor deposition in a reactor that contains plasma generated by use of electron cyclotron resonance. Under properly chosen growth condi-

tions, the large mismatch between the crystal lattices of the substrate and the nitride causes strains to accumulate in the growing nitride film, such that the associated stresses cause the film to crack. The cracks lie in planes parallel to the direction of growth, so that the growing nitride film becomes divided into microscopic growing single-crystal columns. The outer ends of the fully-grown columns can serve as field-emission tips. By virtue of their chemical compositions and crystalline structures,

the columns have low work functions and high electrical conductivities, both of which are desirable for field emission of electrons.

From examination of transmission electron micrographs of a prototype device, the average column width was determined to be about 100 nm and the sharpness of the tips was determined to be characterized by a dimension somewhat less than 100 nm. The areal density of the columns was found to be about $5 \times 10^9 \text{ cm}^{-2}$ — about 4 to 5 orders of magnitude greater than the areal density of tips in prior field-emission devices. The electric field necessary to turn on the emission current and the current per tip in this device are both lower than in prior field-emission devices, such that it becomes possible to achieve longer operational

lifetime. Moreover, notwithstanding the lower current per tip, because of the greater areal density of tips, it becomes possible to achieve greater current density averaged over the cathode area.

The thickness of the grown nitride film (equivalently, the length of the columns) could lie between about 0.5 μm and a few microns; in any event, a thickness of about 1 μm is sufficient and costs less than do greater thicknesses.

It may be possible to grow nitride emitter columns on glass or other substrate materials that cost less than silicon does. What is important in the choice of substrate material is the difference between the substrate and nitride crystalline structures. Inasmuch as the deposition process is nondestructive, an

ability to grow emitter columns on a variety of materials would be advantageous in that it would facilitate the integration of field-emitter structures onto previously processed integrated circuits.

Doping seems to play an important role in the field-emission properties of the columns. The nitride in the prototype device was doped with silicon at a concentration of $5 \times 10^{19} \text{ cm}^{-3}$. Other elements from groups II, IV, and VI of the periodic table could be used as alternative or additional dopants. Doping levels could range from about 10^{16} to 10^{21} cm^{-3} .

This work was done by Abdelhak Bensaoula and Igor Berishev of the University of Houston for Marshall Space Flight Center. For more information, contact Sammy Nabors, MSFC Commercialization Lead at sammy.a.nabors@nasa.gov. MFS-32514-1

HEMT Amplifiers and Equipment for Their On-Wafer Testing

Power levels in CPW circuits can be measured without packaging.

NASA's Jet Propulsion Laboratory, Pasadena, California

Power amplifiers comprising InP-based high-electron-mobility transistors (HEMTs) in coplanar-waveguide (CPW) circuits designed for operation at frequencies of hundreds of gigahertz, and a test set for on-wafer measurement of their power levels have been developed. These amplifiers utilize an advanced 35-nm HEMT monolithic microwave integrated-circuit (MMIC) technology and have potential utility as local-oscillator drivers and power sources in future submillimeter-wavelength heterodyne receivers and imaging systems. The test set can reduce development time by enabling rapid output power characterization, not only of these and similar amplifiers, but also of other coplanar-waveguide power circuits, without the necessity of packaging the circuits.

One of the amplifiers designed and tested at 330 GHz is shown in Figure 1. It is a three-stage unit containing one HEMT in the first stage, two HEMTs in the second stage, and four HEMTs in the third stage, with 1:2 CPW power splitters between the HEMT

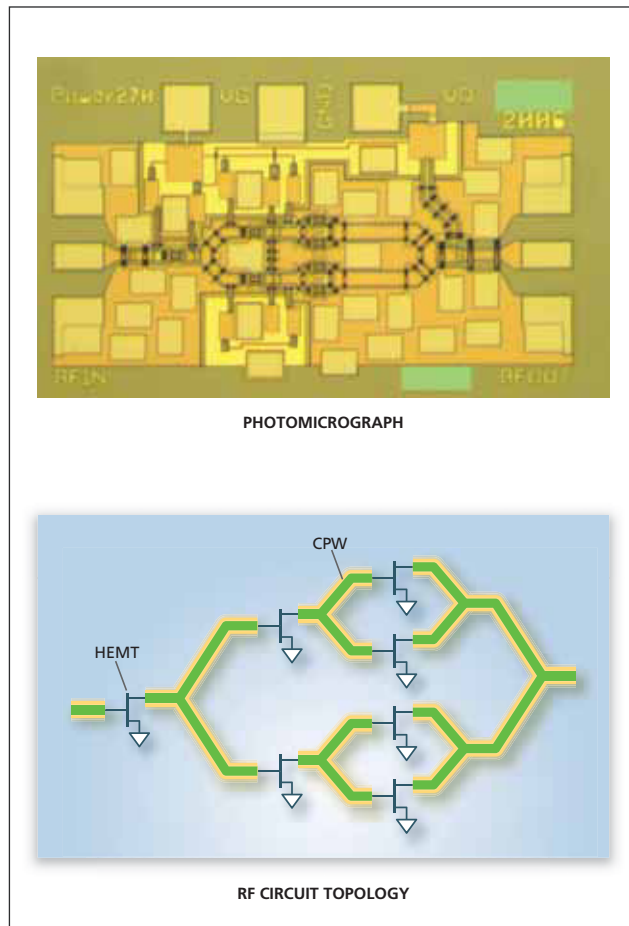


Figure 1. This Three-Stage Amplifier contains HEMTs with RF coupling via CPW structures.

stages. The outputs of the third-stage HEMTs are coupled via a 4:1 CPW power combiner. Each HEMT is a two-finger device having an output periphery of 10 μm per finger, so that the total output periphery per HEMT is 20 μm . Hence, the total output periphery of all four third-stage HEMTs is 80 μm . Because the layout is so extremely compact that individual biasing of each stage cannot be accommodated, the gate and drain bias conductors of all seven transistors are tied together.

Figure 2 schematically depicts the power test set as configured for characterizing this amplifier or another device at 330 GHz at different input power levels. A Gunn oscillator generates a 110-GHz signal, which is then fed via a W-band amplifier and a variable attenuator to a frequency tripler. The output of the frequency tripler is a 330-GHz power source used as the input signal for the amplifier or other device under test (DUT). A calorimeter measures the power output of the DUT. Input and output cou-