waveguide circuit, and an appropriate antenna coupler are fabricated on a single piece of gallium arsenide.

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Submillimeter-Wave Detection with Submicron-Size Schottky-Barrier Diodes

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***Abstract*—Schottky-barrier diode detection has been extended to 7.2 THz (42 μm) using 0.5-μm-diam diodes. The diodes were fabricated on bulk-doped n-type GaAs using electron lithographic techniques; diameters as small as 1000 Å have been achieved. A new approach in Schottky-barrier design, the contact array diode, is proposed. The diode is fabricated from readily available bulk doped material, and a performance is indicated that is competitive to the conventional epitaxial Schottky-barrier mixer well into the submillimeter wavelength region. A scanning electron microscope (SEM) photograph of diode array structures is shown.**

I. INTRODUCTION

THE work described in this paper consists of two parts. The first part summarizes Schottky-barrier diode detection measurements at wavelengths of 42 μm (7.2 THz)–1222 μm (245 GHz) using submicron dimensional Schottky-barrier diodes mounted in an open nontunable mount. Video detection at 42 μm represents the shortest wavelength for Schottky-barrier detection to be reported in the literature. The diodes were 0.5 μm in diameter and were fabricated from nonepitaxial heavily doped n-type GaAs. These ultrasmall, and consequently ultralow capacitance, junctions were prepared using electron beam lithography [1] and have yielded the smallest series-resistance junction-capacitance product to be reported in the literature for a Schottky-barrier diode. The advantages of this doping and structure as well as preliminary video detection and heterodyne mixing measurements at 70–1222 μm have been recently described [2].

The second part of the paper explores the application of this submicron dimensional technology to the fabrication of a Schottky diode mixer employing a tunable mount. A straightforward application of this technology to the fabrication of efficient Schottky-barrier mixers is hampered by conversion loss limitations associated with the imped-

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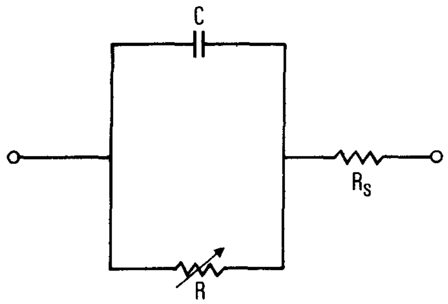


Fig. 1. Equivalent circuit of a single contact Schottky-barrier diode.

ance matchup problem of small diodes [3]. A new approach in Schottky-barrier design, the contact array diode, is proposed as a solution to the impedance problem. Analysis indicates that the new diode will compete very favorably with the conventional epitaxial Schottky-barrier diode well into the submillimeter wavelength region. A scanning electron microscope (SEM) photograph of several preliminary structures is shown.

II. Video Detection and Mixing in an Open Mount

The Schottky-barrier diode can be characterized in terms of the equivalent circuit shown in Fig. 1. The element R represents the nonlinear junction resistance which provides the rectifying volt-ampere behavior necessary for detecting and mixing. The spreading resistance R_s is the resistance in the bulk of the semiconductor which results from the crowding of the current near the metal contact. R_s and the junction capacitance C are parasitic elements and are the primary cause of the degradation in performance of the diode as the frequency is increased. Both elements are unavoidable, but they can be minimized by choosing the proper combination of materials and geometries. The exact design of the diode for optimum performance depends to a large degree on the mount in which the diode is situated.

The measurements reported below were performed on Schottky diodes mounted in an open structure. Such a mount has no provision for tuning out the effect of the junction capacitance C, and consequently, at short wavelengths and with $\omega^2R^2C^2 \gg 1$, diode performance is dominated by C.[1] That is, a reduction in C increases the frequency response and sensitivity of the diodes. Since junction capacitance is proportional to junction area, a reduction in diode size improves its performance. For submillimeter-wave operation, diode diameters less than 1 μm are preferred.

Fig. 2 summarizes the video detection data. The data at wavelengths of 70–1222 μm are comparable to values previously published [2], [4], [5]; the 42-μm measurements represent the shortest wavelength for a Schottky-barrier detector yet reported. The error bars reflect uncertainties in the laser power measurements and the range of signal

[1] It is being assumed that both R_s and $1/\omega C$ are much less than the antenna impedance; this situation is consistent with our measurements. These measurements and their interpretation are too lengthy to be reported here and will be published elsewhere.

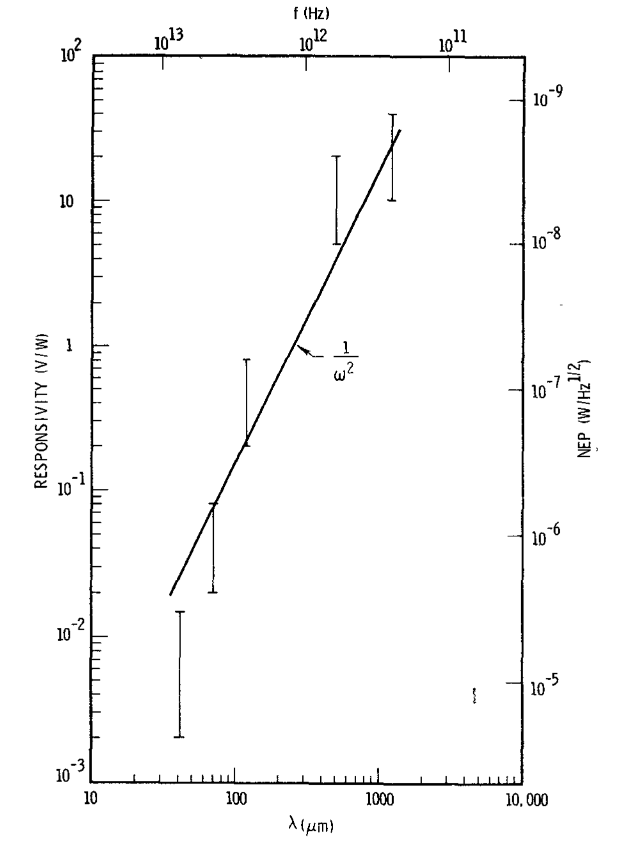


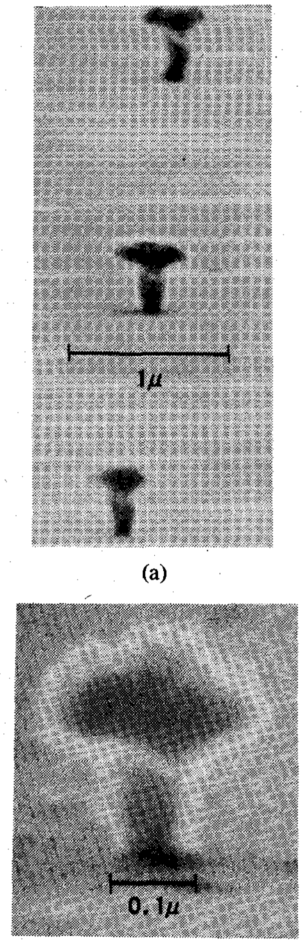
Fig. 2. Measured voltage responsivity and noise-equivalent power versus wavelength and frequency for 0.5-μm-diam 5×10^{18} cm^{-3} n-GaAs Schottky-barrier diodes operating in the video mode with 2 μA of forward bias current and situated in an open mount.

voltages observed with different contacts to the same chip. The performance of the diodes is observed to approximately obey an ω^{-2} dependence, which from elementary circuit theory would be the anticipated result at short wavelengths.

Details of the experimental setup are contained in [2]. The focused laser radiation is coupled to the diode through a whisker antenna which also functions as the contact to the diode. Optimum video detection is obtained using a whisker orientation which selectively excites the main lobe of the long wire antenna.

Heterodyne mixing was observed at the 70–1222-μm wavelengths. Two laser beams were combined in a silicon beam splitter and then focused onto the whisker antenna. The optimum bias condition for mixing was obtained with 200–400 μA of forward current. No mixing has been detected at 42 μm, most likely because the laser power level was lower and the system optical losses were larger at this wavelength.

The diodes consisted of plated Pt contacts 0.5 μm in diameter on uniformly doped nonepitaxial 5×10^{18} cm^{-3} n-type GaAs. The size and doping of the structure yield a calculated zero-bias capacitance C_0 of 1.3×10^{-15} F. This value and a measured dc series resistance R_s of $19 \pm 3\ \Omega$ yield a calculated figure of merit cutoff frequency $f_c = (2\pi R_s C_0)^{-1}$ of 9×10^{12} Hz (a wavelength of 34 μm).



(a)

(b)

Fig. 3. SEM photographs of plated Schottky diodes. The insulating layer normally present has been stripped away. The photographs were taken at steep angles from normal incidence to show the dimensions of the diodes at their base. Fig. 3(b) is a magnified shot of one of the diodes shown in (a).

Because of the higher plasma frequency [6], freedom from transit-time limitations [7], [8], and lower parasitic losses [9], this choice of doping portends a higher frequency capability than an epitaxial structure.

The ultralow capacitance junctions were obtained by fabricating submicron-size junctions using electron lithographic techniques. Relatively large arrays of 2500-Å-diam diodes can be produced routinely. On a limited basis, contact diameters of 1000 Å have been achieved as shown in Fig. 3. These diodes represent the smallest Schottky-barrier diodes yet fabricated and possibly represent the smallest devices, in general, to be reported in the literature.

III. The Contact Array Schottky-Barrier Diode in a Tunable Mount

A tunable mount, such as the standard single-mode waveguide mixer mount with a back short, provides a means of reactively tuning out the junction capacitance C of the diode. As such, coupling to the diode is improved, but R_s becomes an important parameter as well as C. The standard method of minimizing the effects of R_s and C is through the use of epitaxial material wherein a thin layer of moderately doped material has been epitaxially grown on a heavily doped substrate [10]–[12]. The moderately doped layer provides a low capacitance surface with low-noise qualities [13]. In principle, if the layer is sufficiently thin, it provides little series resistance. The large carrier density of the heavily doped substrate also contributes the least possible series spreading resistance. However, a chief difficulty with this approach is the difficulty of obtaining sufficiently thin epilayers with the proper doping profile. Typically, the surface doping is very low, the surface resistivity is very high, and as a result, micron-size junctions can yield very large series resistances.

The single-mode waveguide mixer mount is outstanding in its efficiency of coupling RF radiation to the diode. As such, the mount is the standard mixer package for wavelengths extending over the whole centimeter-to-millimeter region. The success of the coupling mechanism is a direct result of the single-mode concept wherein higher order modes, excited in the region of the whisker and diode, cannot propagate down the guide. In adopting this type of mount for submillimeter wavelengths, the most difficult problems encountered are mechanical in nature; the dimensions are very small and tolerances are very close. Extrapolation to 600 GHz of wall loss measurements reported at frequencies of 35–280 GHz [14], [15] indicates that less than 0.6 dB/cm waveguide loss can be anticipated at this frequency. Our laboratory has designed and nearly completed the fabrication of a single-mode waveguide mixer mount for use at 600 GHz [16], and both submicron single contact diodes and contact array diodes will be tested in this device.

The contact array diode is a new concept in high-frequency Schottky-barrier design, and the rationale for its use will now be discussed and contrasted to the single contact diode. The fabrication of this multiple contact type of diode incorporates submicron diode technology to achieve an efficient low-noise mixer diode using a bulk, moderately doped semiconducting substrate. The moderately doped substrate supplies a low-noise temperature to the diode [13], and the multiple contact design supplies a low series resistance, and hence low conversion loss, to the diode. The use of bulk material eliminates the material limitations and difficulties encountered with epitaxial diodes. The theory and fabrication of the contact array structures are discussed, and some preliminary structures are shown.

A. The Single Contact

The desirable features of the contact array diode are best understood by reviewing pertinent features of the single contact diode. The conversion loss L_c of a mixer in a tunable mount is conveniently expressed as the product of three terms

$$L_c = L_0 L_1 L_2. \tag{1}$$

The intrinsic conversion loss L_0 is the loss arising from the conversion process within the nonlinear resistance of the diode and includes the impedance mismatch losses at the RF and IF ports. The RF and IF parasitic losses, L_1 and L_2, respectively, are the losses associated with the parasitic elements of the diode. These losses are given by [17], [18]

$$L_1 = 1 + \frac{R_s}{R} + \omega^2 C^2 R R_s \tag{2}$$

$$L_2 = 1 + \frac{R_s}{R_2} \tag{3}$$

where ω is the signal angular frequency, R is the signal input impedance of the local oscillator pumped nonlinear resistance, and R_2 is the IF load impedance. The ω^2 dependence of the third term in (2) is responsible for the degradation in the performance of Schottky-barrier mixers at high frequencies. However, both L_1 and L_2 are geometry dependent, and it is this feature that makes the contact array approach to reducing L_c at high frequencies both feasible and attractive.

The spreading resistance of a single contact is given by

$$R_s = \frac{\rho}{2d} \tag{4}$$

where ρ is the resistivity of the semiconductor and d is the diameter of the junction. The junction capacitance C is proportional to junction area, and hence $C \propto d^2$. The impedance R is independent of d since the conditions for optimum coupling constrain R at a value approximately equal to that of the RF source impedance. As a result of the dependences of R_s and C on d, the ω^2 term in (2) is proportional to d^3. Although it would appear that this term could be minimized by reducing the size of the junction, the dependence of L_0 on d can reduce the apparent advantage of very small junctions.

The intrinsic loss L_0 of a Schottky-barrier mixer has been analyzed as a function of diode size [3]. The functional dependence of L_0 on diameter d for a thermionic emitting diode is determined, after some analysis, by the RF source impedance, the temperature of the diode, and the Richardson constant of the semiconductor. The analysis shows that the L_0 of n-GaAs increases rapidly for diameters less than ≈ 2 μm. (The principal advantage of n-GaAs is its comparatively higher mobility, and, hence, its lower resistivity, which results in lower values of L_1.) On the other hand, calculations of L_1 at millimeter and submillimeter wavelengths for n-GaAs show that it is desirable that d be less than ≈ 2 μm. Hence a conflict exists between L_0, L_1, and diode size at short wavelengths, but one that can be resolved by the use of a contact array structure.

B. The Contact Array Structure

The contact array diode is a zero-phased array of small contacts connected in parallel wherein the impedance problem is eased by using a sufficiently large number of contacts. The reduction in spreading resistance afforded by the technique is identical in concept to the multiple contact scheme [19], [20]. It is easily shown for an array of independent diodes connected in parallel that the L_1 of the array is identical to the L_1 of a single diode of that array. The L_0 of the array can be held at a low and constant value by maintaining the total conducting area, i.e., the sum of the areas of the small diodes, at a relatively large and constant value. By holding this total area fixed as the size of the small diodes is reduced and their number increased, L_1 is reduced, and L_0 remains unchanged at its optimum value. Since $(L_1 - 1)$ is proportional to the diameter d of an individual diode, $(L_1 - 1)$ becomes inversely proportional to the square root of the number of diodes in the contact array structure. Hence a structure consisting of a large number of very small diodes achieves the best situation for both L_0 and L_1, and, consequently, for L_c.

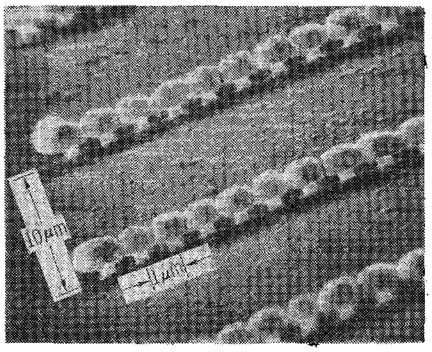


Fig. 4. SEM photograph of preliminary contact array diodes fabricated in a linear geometry.

The contact array concept is more complex than that outlined above because the individual contacts are not completely independent of one another; that is, there is always a finite interaction of the spreading currents of neighboring contacts. A detailed discussion of the design parameters of the contact array structure is beyond the intended scope of this article; however, analysis shows that the optimum geometry for the structure is a linear array. Fig. 4 shows an SEM photograph of several preliminary contact array diodes which have been fabricated in our laboratories. The structure is obtained by overplating the individual diodes until the tops of neighboring diodes come in contact with one another. The insulator which would normally be present has been etched away to facilitate viewing the entire structure. Analysis indicates that excellent performance can be expected with this type of structure at 100, 300, and 600 GHz.

There is also a reliability advantage with the contact array structure. Reliability in the form of maximum power capability and resistance to burnout seems to be the original intent of the multiple contact concept as discussed by Torrey and Whitmer [19]. The concept, in general, provides a built-in redundancy and a reduction in the thermal resistance of the contact which serves to increase the burnout capability of the device.

The contact array technique is also applicable to devices other than the conventional Schottky diode. It has been proposed for the super-Schottky diode [21] as the equivalent circuits of both types of Schottkys are identical. Also, the contact array structure would be beneficial in the construction of a varactor diode where an abrupt junction and a low series resistance are desirable features [22].

In conclusion, the contact array diode has been proposed as a high-frequency low-noise Schottky-barrier mixer. The favorable video response of the small single contact diodes, the demonstrated ability to fabricate complex structures, and detailed analysis suggests that the contact array diode will be a favorable alternative to the epitaxial diode in the near future.

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