QUASI-OPTICAL THz RADAR AND SPECTROSCOPY INSTRUMENTATION BASED ON NONLINEAR TRANSMISSION LINES MMICs

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Abstract The paper presents the design, modelling and manufacturing of a new type of MMIC, a nonlinear transmission line monolithically integrated in a CPW based on GaAs. This device is the key element of the quasi-optical THz instrumentation that will be further developed. A low cost four mask technological process and manufacturing is presented.

INTRODUCTION

Devices able to generate very short time transition electrical signals are essential for the wide-bandwidth time domain spectroscopy, instrumentation, collision avoidance radars and for the all electronic generation of optical signals [1-2]. Therefore, in order to obtain electrical signals with a duration of less than 1-2 picoseconds (at least one order of magnitude shorter than those generated with step recovery or tunel diodes), new concepts and techniques are necessary.

Nonlinear transmission lines MMICs (NLTL MMICs) have demonstrated that picosecond and subpicosecond electrical pulses can be generated using shock and soliton effects [3-4].

NLTL is a MMIC consisting of a planar transmission line periodically loaded with reverse biased Schottky diodes. The diodes induce a voltage variable propagation velocity due to the nonlinear behaviour of their capacitance as a function of the applied voltage. The dispersivity of the propagating waves in NLTL MMIC can be balanced by nonlinearity and the result is a very pronounced compression of the initial excitation.

The NLTL MMIC concept is shown in Fig.1a, while Fig.1b presents the NLTL MMIC in a coplanar wave (CPW). The behaviour of the NLTL is determined by the cutoff frequency of the diodes (f_d) and the Bragg frequency (f_b) of the circuit. We have:

$$f_d=[2\pi R_d C_d(V)]^{-1} \qquad (1)$$

where R_d is the series resistance of the diode and $C_d(V)$ is the capacitance of the diode at the voltage V.

$$f_b=1/(\pi(L_1(C_1+C_d(V))^{1/2}) \qquad (2)$$

where L_1 and C_1 are, respectively, the inductance and capacitance per unit cell of the CPW.

If $f_d \approx f_b$ shock waves are generated, while if $f_d >> f_b$ soliton waves are produced.

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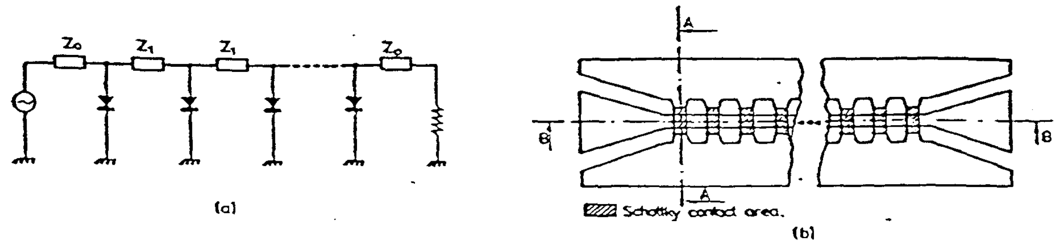


Fig.1 NLTL MMIC: (a) concept, (b) NLTL MMIC in a CPW technique

Starting with 24 dBm input and using the soliton effect, a doubler can attain 17 dBm peak output power at 63 GHz, while a tripler can attain 12.8 dBm peak output power at 108 GHz [3].

Subpicosecond pulses with 880 fs fall time and 3.5 V amplitude have been generated [4] using shock waves. When an ultrabroadband integrated antenna has been excited with these pulses, at a distance of 0.5 m has been detected a signal beyond 3 THz with an amplitude of -130 dBm.

The signal level required for instrumentation, spectroscopy, collision avoidance radars and for the all electronic generation of optical signals should be greater with at least one order of magnitude than -130 dBm. Therefore, a quasi-optical technique is required to increase the signal level. In this respect, a quasi-optical THz radar and spectroscopy instrumentation is represented by an array of NLTL MMICs, each of them having monolithically integrated an ultrabroadband antenna. Such a transmitter with tens of MMICs is able to generate a signal beyond 3 THz with a power level of about +1 dBm.

It will be shown that signals beyond 1 THz can be generated, the designed NLTL MMIC being the key element of the further development of the quasi-optical THz radar and spectroscopy instrumentation.

THE DESIGN OF THE NLTL MMIC

We have designed an NLTL MMIC based on the shock wave effect. The distance between two adiacent diodes is d=90 μm, the delay time between one cell of the periodic structure being $\tau=d/v_{CPW}=0.8$ ps, where $v_{CPW}=1.13\times10^8$ m/s for GaAs. The characteristic impedance of the CPW is 70 Ω. Shock waves are expected in the range of picoseconds, if $R_d=5$-$10\ \Omega$ and $f_b=f_d>240$ GHz.

The shock wave effect can be described as follows: when a negative step voltage propagates along the NLTL, the fall time of the input voltage decreases as a function of the distance. After the propagation through n cells, the transition time is:

$$t_n=t_{in}-n\tau[(1+C_d(0)/C_1)^{1/2}-(1+C_d(-V_{MAX})/C_1)^{1/2}] \quad (3)$$

assuming a step voltage between zero and $-V_{MAX}$.

When the fall time decreases, the dispersion is balanced by the nonlinearity which has the effect of compression due to the voltage-dependent propagation velocity. A stable fall time is obtained when the fall time compression/cell is equal to the fall time broadening/cell. After that, the resulting shock wave propagates unchanged in shape along the NLTL. We have chosen n=45

diodes and the simulation done on a MDS-Hewlett-Packard are displayed in Fig.2 for the output of the NLTL MMIC in frequency and time domain. In the simulations presented in Fig.2 the device has been excited with a sinusoidal wave at 18 GHz and having amplitudes of 3, 3.5 and 4 V. It can be observed that the fall time of the output voltage is 2.2 ps and it shows, for V_{in}=4 V, an almost flat spectrum up to 180 GHz with a loss of 15 dB [5]. The efficiency of the second harmonic is 34% and could be optimized to be 51% (for d=70 μm), while the efficiency of the third harmonic (54 GHz) is 44%. At 108 GHz we have obtained an efficiency of 31% (5^{th} harmonic). The efficiency has been calculated as $100\% \times 10^{\text{harmonic level [dB]}/20}$.

Taking into account that the performance limitations are due to the diode losses, it has been shown [4] that at 77 K the fall time decreases with a factor of 2.3. At 77 K the device will have a fall time of 990 fs with a spectrum beyond 2 THz. The simulation was performed for a Schottky varactor diode with a voltage varying capacitance: $C(V)=C_0/(1-V/V_0)^p$, where p=0.87, C_0=40 fF, V_0=0.8 V. The losses due to CPW and GaAs have been included in the simulation.

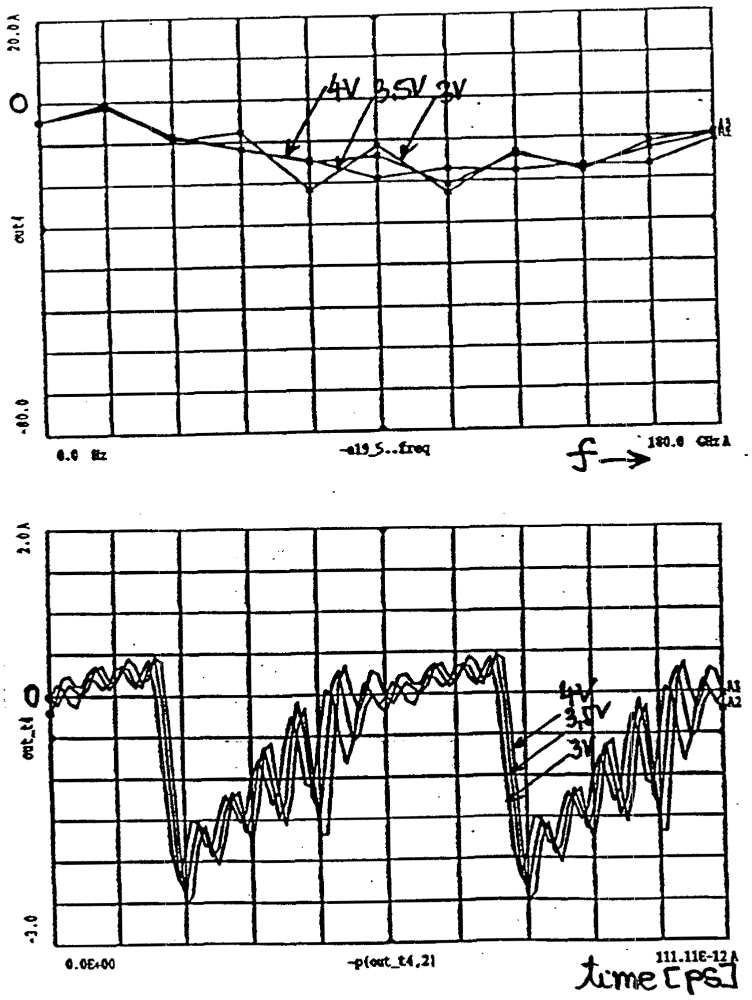


Fig.2 The simulation of NLTL MMIC

DEVICE REALIZATION

Rodwell et al [6] have proposed a structure manufactured using MBE, ion implantation and proton isolation. We have proposed and manufactured a structure using more accesible and less expensive facilities. Vapor phase epitaxy is used for wafer preparation and conventional mesa etching is used for isolation.

The device is prepared on GaAs epitaxial structures grown by chloride type VPE technology, using S doping. On a semi-insulating substrate different succesive layers have been grown. First an undoped, high resistivity buffer layer was grown with a thichness less than 2 μm. Then an n^+ layer was grown with an impurity concentration of about $1x10^{18}$ cm^{-3} with a thickness of about 1 μm. Next a very thin undoped layer follows. The thickness is chosen to reach an electron concentration of about $(2...5)x10^{16}$ cm-3 or less. Finally a series of thin layers has to be grown with increasing impurity concentrations in such a way that the carrier concentration profile shows a hyperabrupt varactor diode profile. Near to the top surface the concentration in the layer is chosen according to two requirements: the breakdown voltage of the Schottky diode must be 5 V and the depletion region must be below 0.2 μm. This part of the structure cannot be characterized directly by concentration profilometry, so other structures have been grown for characterization. A typical concentration profile is shown in Fig.3.

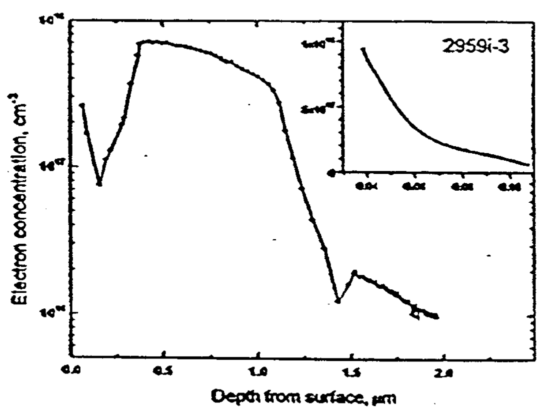


Fig.3 The impurity profile of the GaAs wafer

A four mask technological process was developed.

The first mask is the mesa mask which defines the areas on which the Schottky diodes array will be located. The mesa etch reaches the SI substrate. A CVD SiO_2 0.5-1 μm layer covers the wafer and, with the second mask, the windows for ohmic contact formation are opened. The ohmic contact (AuGeNi) is deposed directly on the n^- layer or, for smaller series resistance, on the n^+ layer. This requires the removing (by etching) of the n^- layer before metal deposition. A lift-off technique is used in the metallization process.

The next step consists in opening of the Schottky contacts in the SiO_2 layer.

In our structure, silicon dioxide is also removed in the groves between the Schottky diodes, excepting small areas around the mesa valleys. This is a difficult process because it requires a photolithographic process on a nonplanar surface. Silicon dioxide has to be removed in the 7-8 μm large windows on the top of the

mesas and in the same time from the large groves between the mesas. A special multilevel resist planarization technique was used for this process.

After the Schottky metal deposition (Al, TiAu or CrAu), the coplanar transmission line with a 12 μm width central conductor is realized using a lift-off process. A cross section of a cell of the device is presented in Fig.4. Scanning microscope photos of the devices are presented in Fig.5 and Fig.6.

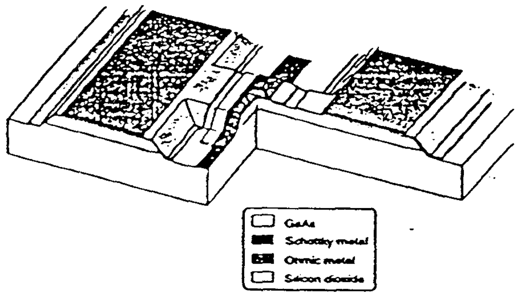
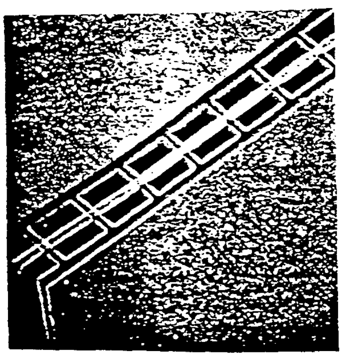
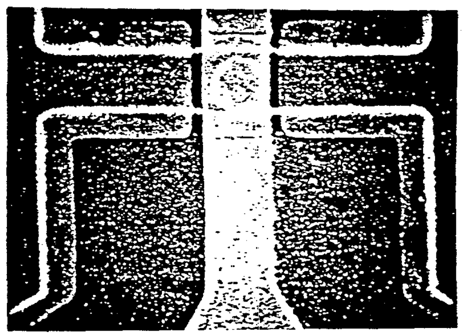


Fig.4 NLTL MMIC one-cell cross-section





Figs.5,6 Scanning electron microscopy of the device

In order to have a continuity of the very long (≈ 5 mm) Schottky metallization line it is necessary to have a suitable mesa angle (a gradual slope profile). In the case of our device, the mesa etching is about 2 μm deep and the metallization has to cross it over 1x45 times.

Due to the anisotropy of most etchants of GaAs (especially those based on the H_2SO_4-H_2O_2-H_2O system) there is a suitable direction which has to be used. The device has to be oriented with the Schottky metallization line along this direction. If the device is not oriented in the good direction discontinuities can appear in the line. This is a typical deffect which has to be avoided (Fig.7).

A tpical C-V characteristic of the device is presented in Fig.8.

A 40 fF zero bias capacitance per diode has been obtained.

In order to contact the device in a test or application fixture, the dimensions of the CPW Schottky transmission line is extended by a tapered section (50 Ω characteristic impedance) to 0.6 mm width of the central line.

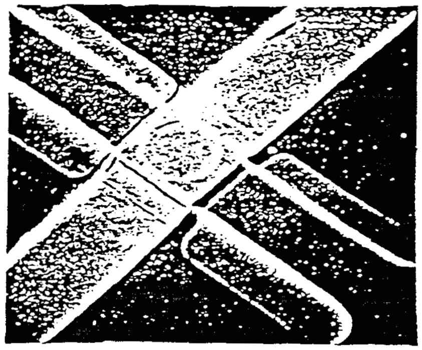


Fig.7

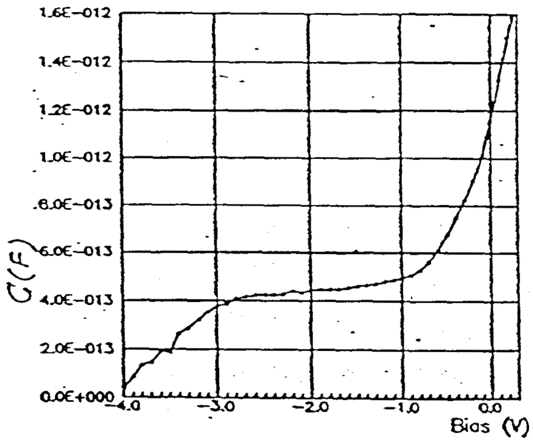


Fig.8 C-V characteristic of the realized structure

CONCLUSIONS

The design, modelling and manufacturing of a NLTL MMIC for compression in the picosecond time-domain and frequency multiplication in the millimeter wave range is presented.

These results show the possibility of using the NLTL MMIC in a quasi-optical THz radar and spectroscopy instrumentation based on NLTL MMICs.

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