Millimeter frequencies generation on a travelling MMIC Schottky diode array and application in an automotive sensor

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Abstract

The paper presents the design, modelling and manufacturing of a new type of MMIC a nonlinear transmission line which consists of 45 Schottky diodes monolithically integrated in a CPW based on GaAs. A four masks technological process was developed, using a special hyperabrupt n^-n^+ profile on a semi-insulating GaAs substrate.

Introduction

Devices able to generate very fast transition-time electrical signals are essential for wide-bandwidth time domain and microwave instrumentation. In order to obtain pulses one order of magnitude faster than those generate with step recovery diodes or tunnel diodes a periodic nonlinear transmission line MMIC is designed. Due to the dispersive and nonlinear character of wave propagation, this device has unique properties in the field of picosecond pulse technique and millimeter wave generation [1,2,3].

The designed MMIC is manufactured on a GaAs semi-insulating substrate using VPE and medium resolution photolitographic processes.

Modelling of the NLTL

The nonlinear transmission line (NLTL) is a MMIC consisting of a planar transmission line periodically loaded with reverse biased Schottky diodes (Fig.1.a). Due to the nonlinear voltage-variable capacitance behaviour of the Schottky contact under large signal conditions, the transmission line is periodically loaded with nonlinear elements which introduce voltage-variable propagation velocities. In Fig.1.b the NLTL in a coplanar waveguide (CPW) technique is shown and in Fig.1.c the equivalent circuit for modelling purpose is presented. The behaviour of the NLTL MMIC is determined by the cutoff frequency of the Schottky diode (f_d) and the Bragg frequency (f_b) of the circuit. In this respect, if f_d has the same order of magnitude as f_b, shock waves are generated, while if $f_d >> f_b$ soliton waves, described by a Korteweg de Vries equation [2], are generated. Taking into account that

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

and

$$f_b = 1/(\pi\sqrt{L_l(C_l + C_d(V)}) ,$$

where R_d is the series resistance of the Schottky diode, $C_d(V)$ is the capacitance of the Schottky diode at the

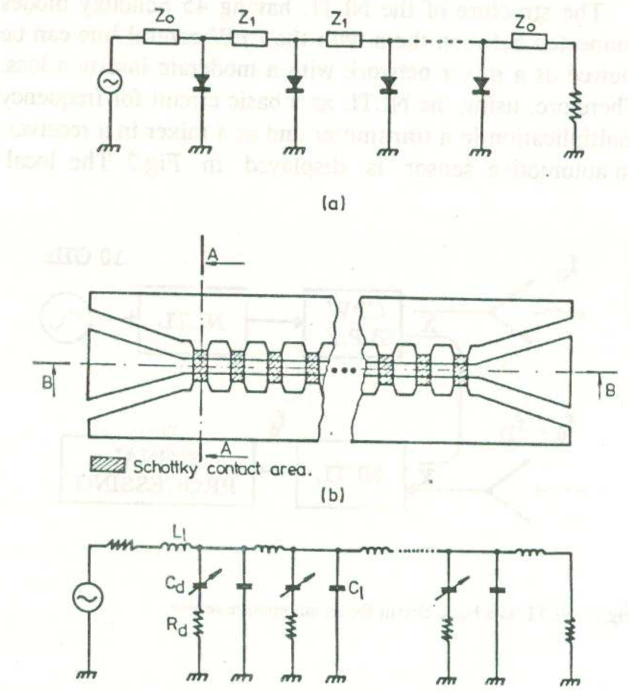

Fig.1 : NLTL MMIC. (a) NLTL concept, (b) NLTL MMIC in a CPW technique, (c) the equivalent circuit of the NLTL MMIC in the CPW technique.

voltage V and L_l , C_l represent the inductance and capacitance per unit cell of the CPW, we have chosen a diode of 40 μm^2 area and a periodicity between two diodes of d=90 μm. The delay time of one cell of the periodic structure is $\tau = d/v_{CPW}$, where $v_{CPW}=1.13\times10^8$ m/s for GaAs. In this manner $L_l=\tau/Z_l=55.3$ pH and $C_l=\tau/Z_l=11.2$ fF have been computed for $\tau=0.8$ ps and $Z_l=70\ \Omega$ (Z_l is the characteristic impedance of the CPW). For $R_d=10\ \Omega$, $f_b=f_d=240$ GHz, shock waves are expected in the range of picosecond time-domain.

If a negative step input voltage is propagating along the NLTL, the fall time of the input voltage will decrease as a function of distance due to the dependence of the instantaneous voltage of the Schottky diode. After the propagation through n cells, the transition time will be

$$t_n = t_{in} - n\tau\left(\sqrt{1 + C_d(0)/C_l} - \sqrt{1 + C_d(-V_{\max})/C_l}\right)$$

assuming a step of the input voltage between zero and $-V_{max}$.

When the fall time is decreasing, 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 ratio becomes equal to the fall time broadening / cell ratio. After that, the resulting shock-wave propagates unchanged in shape along the NLTL. We have chosen n=45 diodes, having as a result the decrease of the input fall time with about 21 ps. For a sinusoidal wave of 10 GHz having a fall time of 30 ps, the compression factor is 3.4. Therefore, frequencies up to 35 GHz can be obtained through shock -wave generation.

The structure of the NLTL having 45 Schottky diodes connected between them with the CPW central line can be viewed as a mixer network with a moderate insertion loss. Therefore, using the NLTL as a basic circuit for frequency multiplication in a transmitter and as a mixer in a receiver, an automotive sensor is displayed in Fig.2. The local

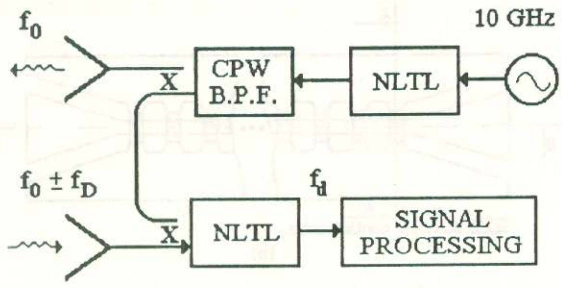

Fig.2 : NLTL as a basic circuit for an automotive sensor.

oscillator has the same frequency as it is generated by NLTL MMIC and is pumped in the NLTL MMIC mixer through a CPW coupler.

Device manufacturing

Rodwell et al [3] 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 thickness not more than 2 μm. Then an n^+ layer was grown with an impurity concentration of about 1×10^{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 $(2...5)\times10^{16}$ 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 above 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.

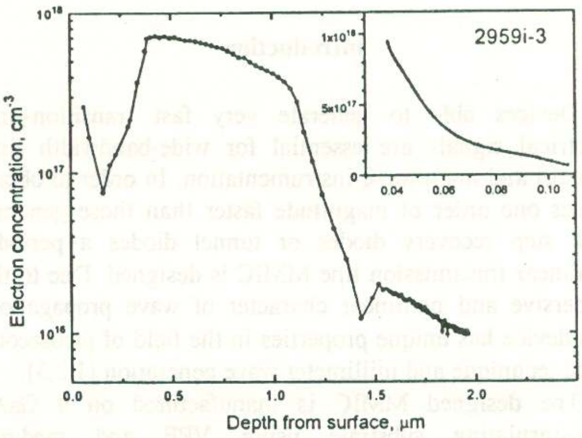

Fig.3 : The impurity profile of the GaAs wafer.

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 7-8μm 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.

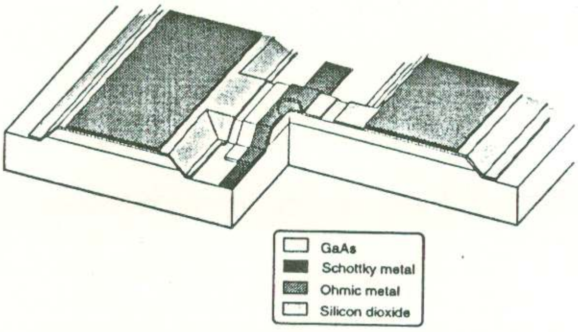

Fig.4 : The cross-section of a cell of a NLTL MMIC.

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.

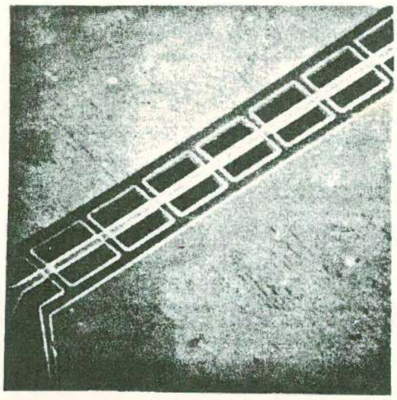

Fig.5 : Scanning electron microscope photos of the device.

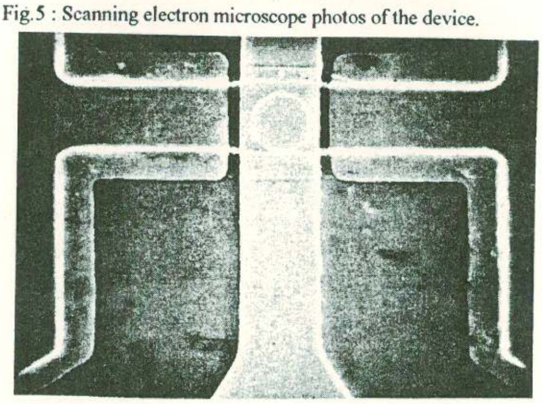

Fig.6 : Scanning electron microscope photos of the device.

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).

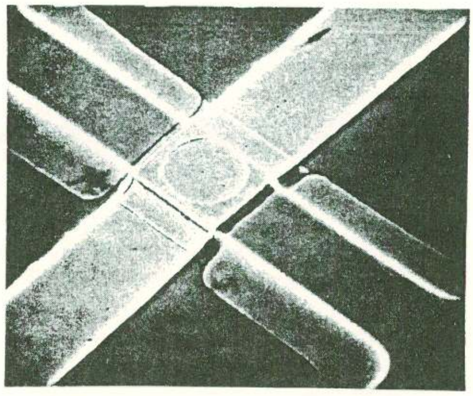

Fig.7 : A typical deffect for a bad orientation of the device on the wafer.

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

A 30 fF zero bias capacitance per diode has been obtained.

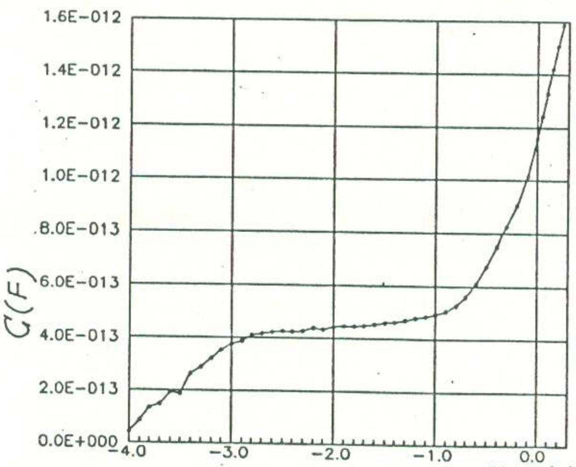

Fig.8 : C-V characteristic of the realized structure.

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.

Conclusions

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

The technological realization of a special profiled GaAs epitaxial wafer and patterns for a NLTL having 45 hyperabrupt Schottky diodes are also presented.

These results show the possibility of using the NLTL MMIC in a automotive sensor in the range of the millimeter waves.

References

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