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725 GHz Sampling Circuits Integrated with Nonlinear Transmission Lines

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We have measured $0.68\,ps$ electrical step functions, the fastest reported to date, generated by nonlinear transmission lines (NLTLs) integrated with sampling circuits which have a $3\,dB$ bandwidth of at least $725\,GHz$. From the measured waveforms, the average velocity of the depletion edge of the varactor diodes on the NLTL is calculated to be $2.1\cdot10^{7}\,cm/sec$. Because the other time constants in the circuit are much smaller than the measured $0.68\,ps$, this velocity saturation is believed to be the limiting phenomenon of the circuit performance.

An NLTL is an electrical step function generator consisting of a high-impedance transmission line periodically loaded with varactor diodes [1]. The NLTL per-diode propagation delay $T_{delay} = \sqrt{L_{line}\cdot(C_{line}+C_{diode}(V))}$ is a function of the diodes' capacitance, and both decrease with increasing reverse bias voltage. The falling edge of the waveform becomes steeper during propagation since the delay for the waveform peak is greater than for the trough. A shock wave is formed whose transition time is limited by the diodes' cutoff frequency $f_c = (2\pi R_d C_d)^{-1}$ and the Bragg frequency $f_{Br} = (\pi\cdot T_{delay})^{-1}$ that arises from the NLTL's periodicity.

To make f_{Br} high the diode separation must be decreased, and this spacing becomes limited by the diodes' physical size. As the line dimensions are reduced, the diodes' pad parasitics contribute a large fraction of C_{line} and lower f_{Br}. To address both these problems, coplanar waveguide (CPW) transmission lines were fabricated with the center conductor raised off the substrate. Others have used a similar technique to reduce loss at the line input [2], but the impact is much greater at the high frequency output end. By elevating the center conductor $3\,\mu m$ above the substrate, the wave velocity is doubled and, hence, for the same physical separation between diodes, f_{Br} is doubled.

The process flow consists of forming ohmic contacts, ion implanting to provide isolation, depositing metal for the Schottky contacts and CPW ground planes, and then applying a layer of polyimide. The polyimide is subsequently etched in an O_2 R.I.E. system until $\approx 0.2\,\mu m$ of the Schottky metal is exposed. The posts for the air bridge lines are formed on top of the polyimide and provide the contacts to the tops of the diodes. After electroplating the air lines, the polyimide is removed, leaving the contacts between the CPW and the diodes in air, substantially reducing the parasitic capacitance.

By contacting the diodes this way, a small Schottky contact can be placed in the middle of a larger active region. The regions outside the active areas are H^+ implanted to render them semi-insulating, and the lateral straggle of the ions damages the active regions near the mask edge. By contacting the diodes from the top, $1\,\mu m \times 1\,\mu m$ sampling diodes were fabricated that suffered no performance degradation from the H^+ lateral straggle.

The NLTLs are designed to have $f_{Br} = 1500\,GHz$ and the $1\,\mu m$ diodes on GaAs with an active layer of $N_D = 1\cdot10^{17}\,cm^{-3}$ have $f_c = 4\,THz$ [3]. NLTLs providing separate strobe and test signals are integrated with sampling circuits to provide for on-wafer measurements. The bandwidth of the sampling circuits is determined by the aperture time of the strobe pulse and the RC time constant of the sampling diodes, both of which are $<0.2\,ps$.

The sampled waveform has a $3.7\,V$ step with a $0.68\,ps$ $10\%-90\%$ falltime. In previous work, where the time constants of the sampling circuits and the NLTLs were comparable, a simple sum-of-squares deconvolution has been used to determine the sampler bandwidth. Using that method here gives a conservative estimate for the sampler bandwidth of $725\,GHz$.

In the NLTL's varactor diodes, the depletion edge moves $145\,nm$ in $0.68\,ps$, giving an average velocity of $2.1\cdot10^{7}\,cm/sec$. Because all other time constants in the circuit are much lower than this, the velocity saturation, which has been analyzed by others [4], appears to be the limiting phenomenon. Similar circuits will be fabricated on material with $N_D = 3\cdot10^{17}\,cm^{-3}$ and a speed enhancement is expected because of the $\sqrt{3}$ reduction in the distance the depletion edge will have to move.

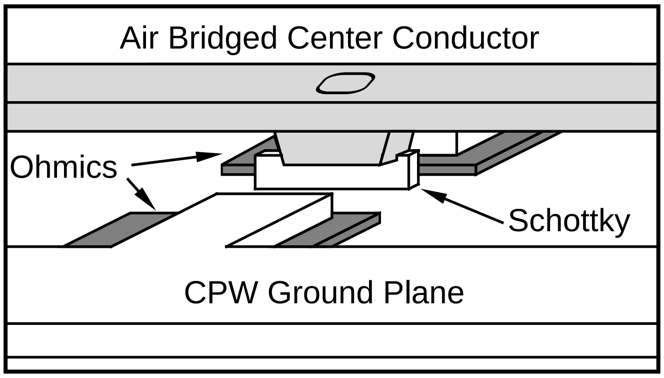

Figure 1: Perspective drawing showing the air bridged center conductor contacting the top of a diode. The Schottky contact is kept well away from the edge of the H^{+} implanted region, which ends outside the ohmics.

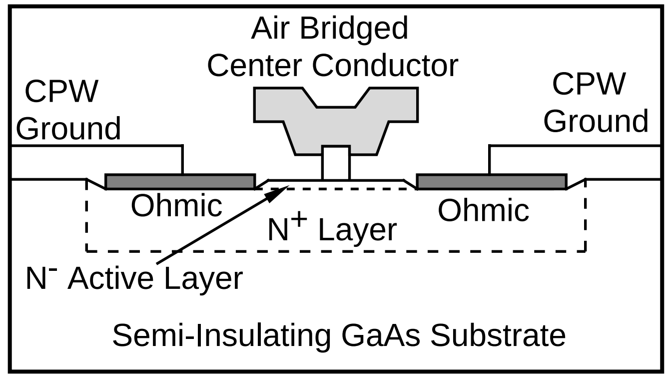

Figure 2: Cross section of the air bridge contacted diode. A layer of polyimide is used to keep the post off the substrate during electroplating. The ohmic contacts are recessed through the N^{-} active layer to a heavily doped N^{+} buried layer.

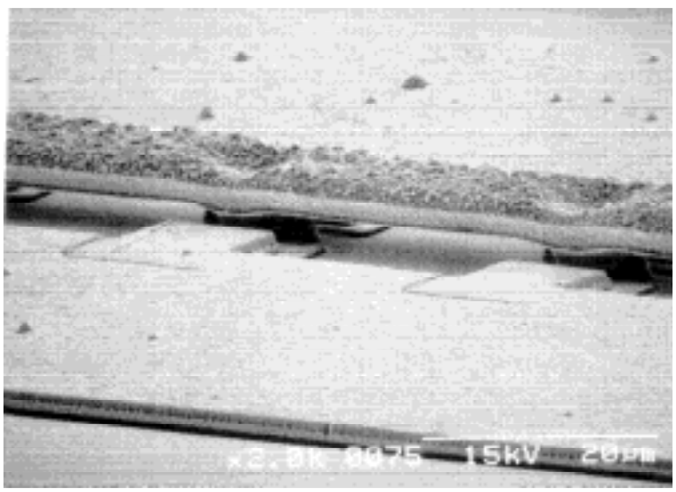

Figure 3: S.E.M. image showing the air bridged center conductor of the coplanar waveguide contacting the tops of the diodes on the NLTL without touching the substrate.

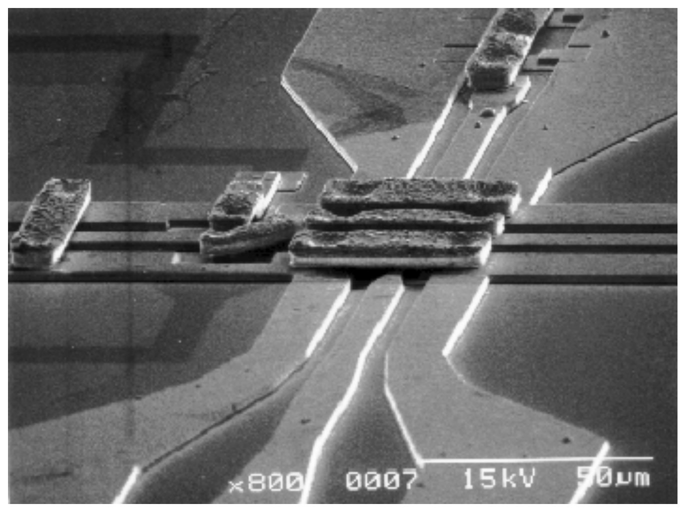

Figure 4: S.E.M. image of the sampling circuit and the output end of the NLTL that provides the strobe pulse to the two $1\mu m \times 1\mu m$ sampling diodes.

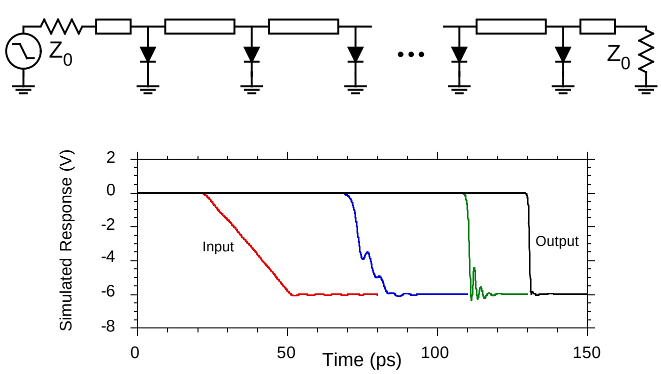

Figure 5: Schematic diagram of a nonlinear transmission line and a SPICE simulation showing the formation of a shock wave as a negative-going edge propagates down the line.

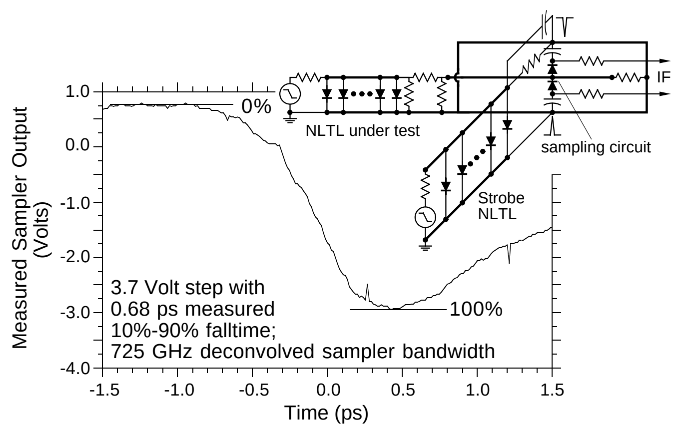

Figure 6: Measured output from a sampling circuit integrated on wafer with two NLTLs showing the $0.68\,ps$ step function. The inset shows a schematic diagram of the circuit.

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[2] Shakouri, et al., *Electronics Letters*, vol. 29, no. 6, 18 March, 1993.
[3] Allen, et al., *Electronics Letters*, vol. 29, no. 25, 9 December, 1993.
[4] Kollberg, et al., *Microwave Theory and Techniques*, vol. 40, no. 5, May, 1992.