FLIP–CHIP MOUNTED SILICON–BASED IMPATT DIODES FOR AUTOMOTIVE APPLICATIONS

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ABSTRACT

We present the first silicon–based active antenna based on flip–chip mounted Impatt diodes. Our results show that flip–chip integration of Impatt diodes is a very promising alternative to monolithic integration since expected output power and heat removal is improved significantly. Compared to active antennas based on monolithic integration, the chip size of the novel flip–chip device is reduced by a factor of 50. Due to this fact, considerable reduction of manufacturing costs is expected.

INTRODUCTION

Active integrated antennas are considered as key elements in future automotive radar applications such as collision avoidance [1], ground–speed measurement [2] or determination of road condition [3]. In the prospected automotive millimeter wave bands at 61 and 76 GHz, only few self–oscillating active antennas have been reported [4,5]. Those designs were based on monolithically integrated Impatt diodes, coupled to resonant microstrip patch dipoles. The radiated RF power of planar Impatt oscillators, however, never reached the levels generated by diodes mounted on diamond heat–sinks. The primary reason for that discrepancy is presumably the lower thermal conductivity of silicon compared to diamond. Therefore, maximum operation currents and related impedance levels are smaller which, finally, results in the lower output power levels observed. To overcome these difficulties we have investigated a hybrid flip–chip concept. This new setup aims at an improved heat removal compared to the monolithic case which, lastly, gives higher yields in output power and efficiency.

FLIP–CHIP MOUNTING OF IMPATT DIODES

In our novel flip-chip configuration (Fig. 1), the Impatt layers are grown on 100 mm diameter highly doped silicon substrates. After thinning of the processed wafers, single chips with a size of 220x250 μm are mounted to the antenna structure in flip–chip technology. When assembled, one contact of the diode is connected to a gold plated finger in the middle of the antenna structure while the highly doped bulk substrate is connected to the surrounding contact fingers. Efficiency of heat removal is raised as the Au finger works additionally as a heat spreader. Furthermore, top heat spreading is also expected to be significantly improved.

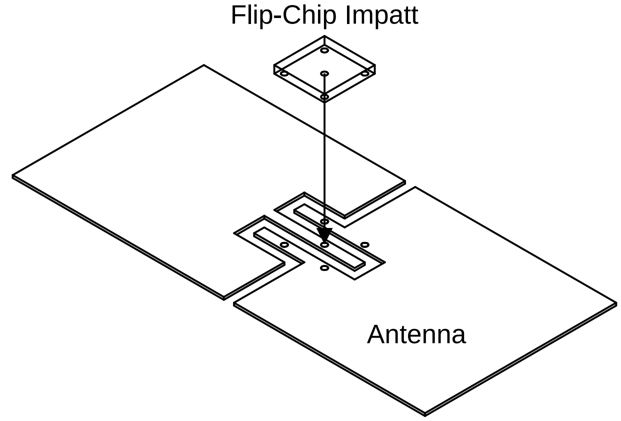

Fig. 1: Concept of the flip-chip mounted Impatt diode.

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Numerical simulations show that the thermal resistivity of this setup is about two to three times lower compared to monolithically integrated devices. Fig. 2 shows a photograph of a monolithically integrated Impatt diode, used typically in active antennas for comparison. The Impatt diode is electrically connected via air bridge (top contact) and buried layer (bottom contact). Heat generated under operation conditions is flowing through the silicon substrate and, to a smaller extent, through the air bridge that acts as a top heat spreader.

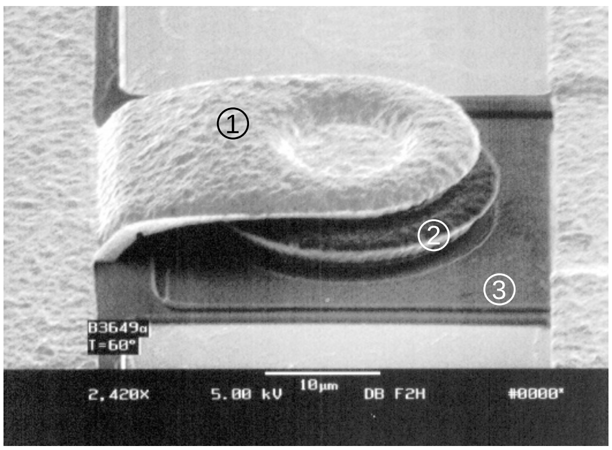

Fig. 2: SEM of monolithically integrated Impatt diode. (1) Airbridge (top contact), (2) Impatt diode, (3) Buried layer (bottom contact).

IMPATT DEVICE FABRICATION

The flip–chip IMPATT diodes are fabricated on highly doped 100 mm n^+ – silicon substrates. The layer sequence of double drift Impatt diodes is grown by silicon molecular beam epitaxy (Si–MBE). The fabrication of the flip–chip Impatt diodes is done with only two mask levels. With the first mask level the gold bumps for the top mesa contact of the diodes are formed using a photolithographic step and gold electroplating. Gold bump heights up to 8 µm are achieved. With these gold bumps as mask, the mesa etch is performed with an isotropic dry etch process. The substrate contact is evaporated as a self-aligned contact. This metallization also serves as starting layer for electroplating the base bumps, which are defined by a photolithographic step with the second mask level. Gold electroplating is performed with the same height as the mesa contact. Fig. 3 shows a scanning electron micrograph (SEM) of the fabricated flip chip Impatt diode. The center bump is the mesa top contact of the diode, the surrounding bumps are the base contacts. These diodes are flip-chip mounted on the patch antenna structure of Fig. 4. The patch antenna structure is fabricated on a high resistivity silicon substrate with a thickness of 125 µm and backside metallization. Gold metallization thickness on the front side is 4 µm.

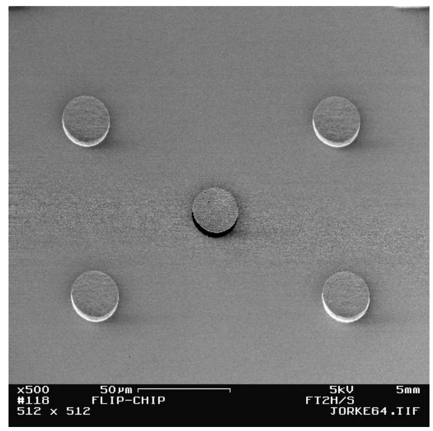

Fig. 3: SEM of a flip-chip Impatt device. The Impatt diode is located in the middle of the chip while the four surrounding bumps provide ground contact.

APPLICATION: SELF–OSCILLATING, ACTIVE ANTENNA

To demonstrate the capabilities of flip–chip mounted Impatt diodes, we built a self–oscillating active antenna. To start oscillation, the Impatt diode's impedance $\underline{Z}_{\text{IMPATT}}$ has to be matched to the impedance of the planar resonator $\underline{Z}_{\text{ANTENNA}}$. The oscillation condition

$$\underline{Z}_{\text{IMPATT}} + \underline{Z}_{\text{ANTENNA}} = 0 \qquad (1)$$

has to be met at the desired operation frequency of 61 GHz. The design of the antenna basically resembles the design reported in [4], however certain changes had to be made to mount the flip–chip device (Fig. 4).

As the flip–chip Impatt diode chip covers a certain part of the antenna, a sophisticated multilayer full–

wave analysis by the method of moments (HP MDS/Momentum) was done. In this simulation, we used a three layer model for the substrate. Layer 1 consisted of a 125µm silicon substrate with back–side metalization. The gold bumps were modeled as a via–layer (layer 2) of 30µm thickness and $\varepsilon_r = 1$. As third layer, we used a solid metal surface as a model for the metallization of the flip–chip device. The simulation was performed over the frequency range from 20 to 100 GHz. Fig. 5 shows the impedance as seen by the Impatt diode located between layer one and three.

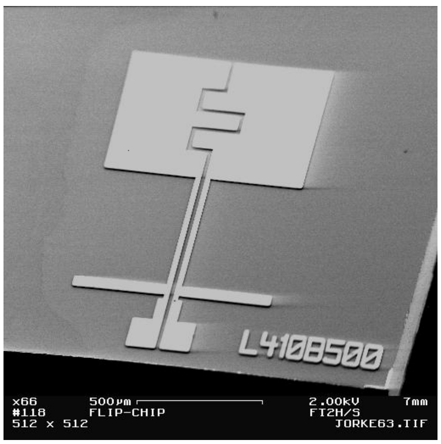

Fig. 4: SEM of 61 GHz patch antenna design, prepared for mounting the flip-chip Impatt device.

The antenna provides an impedance of 3,9 +*j* 37,9 ohms at the design frequency of 61 GHz. As the impedance of the Impatt diode is - 4,3 -*j* 38 ohms for typical bias currents of 19..40 mA, the active antenna starts oscillation. Though some antenna and bias filter resonances appear at various frequencies, the oscillation condition is only met at 61 GHz.

EXPERIMENTAL RESULTS

The considered flip-chip devices have been mounted by thermal compression bonding on high resistivity silicon substrates which carry the planar resonator structure. The rf spectrum of an oscillator with a diode diameter of 22 µm is depicted in Fig. 6. The oscillation frequency can be shifted by either changing the diode diameter or the length of the dipole patches. Measured oscillation frequency of assembled oscillators is collected in Figs. 7 and 8. The oscillating frequency of flip-chip mounted oscillators with the same dimensions deviates by no more than 300 MHz, using diodes with the same area. The measured cw rf power of the oscillators is 50 mW at a dc current density of 12 kA/cm^2.

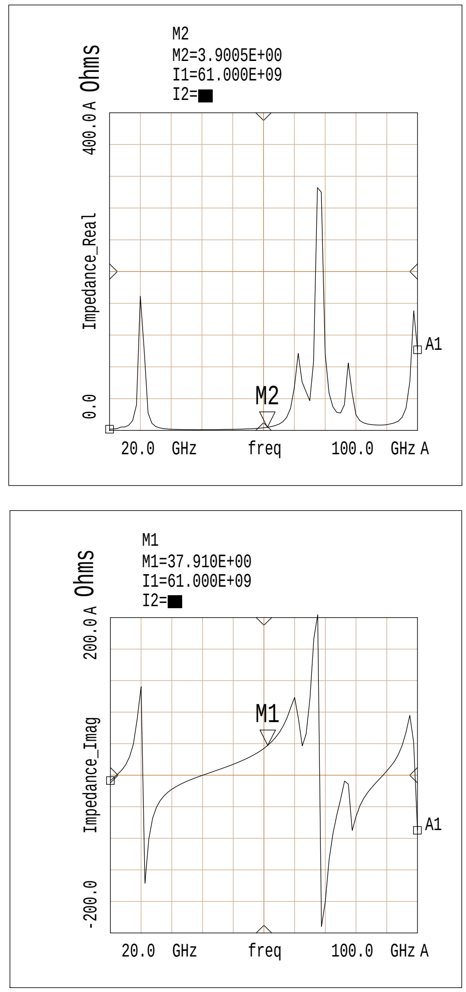

Fig. 5: Real (top) and imaginary (bottom) part of the antenna input impedance.

For an oscillator with a dipole length of 390 µm and a diode diameter of 22 µm, the oscillating frequency has been designed to be 61 GHz. The discrepancy to the measured frequency of 64.3 GHz might mainly be due to the bump height of 30 µm, which has been assumed in the simulations. This results in a higher imaginary part of the calculated load impedance compared to the realized oscillator with a bump height of 8 µm.

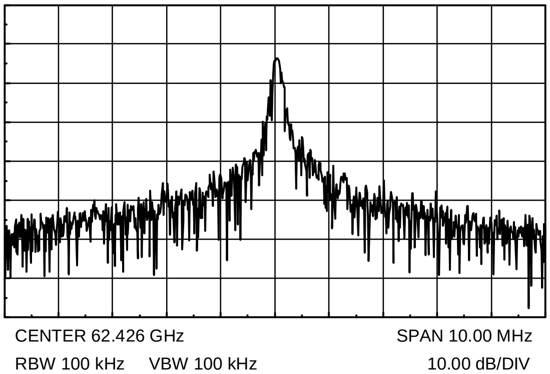

Fig.6: Spectrum of a flip-chip assembled Impatt oscillator.

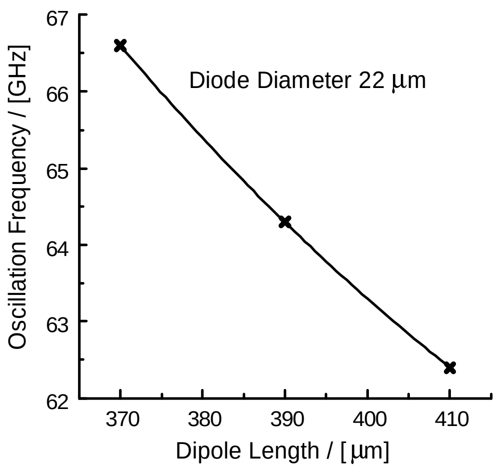

Fig. 7: Measured oscillation frequency, length of the dipole patches is varied. Diode diameter is 22 µm.

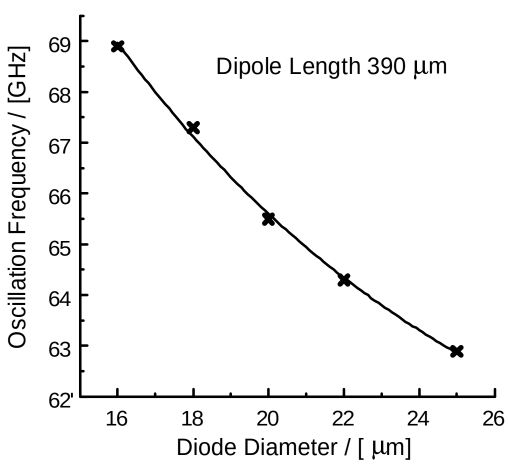

Fig. 8: Measured oscillation frequency for various diode diameters. Dipole length is 390 µm.

CONCLUSION

We developed a self–oscillating 61 GHz active antenna based on a flip–chip mounted Impatt diode. The output power of the flip–chip Impatt device meets the requirements for the envisaged applications and is obtained due to the improved thermal stability compared to monolithical realizations. Furthermore, reduction of the manufacturing costs is obtained by reduction of the active chip size. The flip-chip technique represents the platform for a future millimeterwave integration concept, including e.g. SiGe-HBTs, varactors, Schottky- and PIN-diodes on a single substrate.

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