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Fabrication of Integrated Planar Gunn Diode and Micro-cooler on GaAs Substrate

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***Abstract*—We demonstrate fabrication of an integrated micro cooler with the planar Gunn diode and characterise its performance. First experimental results have shown a small cooling at the surface of the micro cooler. This is first demonstration of an integrated micro-cooler with a planar Gunn diode.**

Keywords—micro cooler; Gunn diode; thermionic cooler;

I. INTRODUCTION

PLANAR Gunn diodes with GaAs/AlGaAs heterojunctions have successfully demonstrated oscillation in the transit-time fundamental mode at 108 GHz [1]. Numerical simulation based on a self-consistent Monte Carlo method has shown the mechanics of Gunn domain formation and transport in such devices [2]. These novel devices have great potential as integrated millimeter-wave or terahertz signal sources. This is because the lithographically determine device anode and cathode spacing L_{ac} and can be reduced to sub-micrometer dimensions to yield higher frequency of transit-time mode oscillation [3]. The reduction is L_{ac} has to scale with higher doping level to achieve smaller domain size. This directly results in an increase in electron current density in these devices, significantly increasing the heat generated in the channel leading to increased operating junction temperature of the device. High junction temperature will contribute to increased scattering in the channel and reduced electron velocity, increased noise as well as lower impact ionisation threshold. The early onset of impact ionisation would result in early device failure. Also, GaAs is known to have poor thermal conductivity compared to silicon (Si), which means passive heat removal would not be enough for stable Gunn diode operation. The presence of a micro-cooler only few micron away from the active channel would improve the heat removal and as a result planar Gunn diodes would be operating in a thermally stable environment. Recently similar approach has been implemented is some of the compound semiconductor devices [4]. However, there is no previous report on integrated planar Gunn diodes with a micro-cooler. Hence this work would be a significant step to address the stable operation for short L_{ac} Gunn devices.

We are presenting for the first time an integrated thermionic micro-cooler integrated with a planar Gunn diode. We will describe the layer structure of the planar Gunn diode with integrated thermionic micro cooler followed by the device fabrication and finally first experimental measurement of the micro cooler.

II. EXPERIMENTAL

A. Planar Gunn Diode and MicroCooler Design

In conventional vertical Gunn diode the cathode contact is at the bottom and also acts as the heat-sink. The substrate is removed in that case and device placed in a metal cavity. However, planar Gunn devices are designed to be integrated with on chip electronic components on a substrate. In this case, placement of heat sinking will always be a long distance away from the active channel of the devices. An integrated micro-cooler is one possible solution to improve the heat removal in a planar structure. Figure 1 shows schematically the integration of a micro cooler for planar Gunn diode on a semi-insulating substrate. The planar Gunn diode and micro cooler are electrically isolated from each other by using a 5 µm thick un-doped GaAs separation layer. Monte Carlo simulations were carried out to estimate the smallest possible separation layer to achieve electrical isolation between two devices.

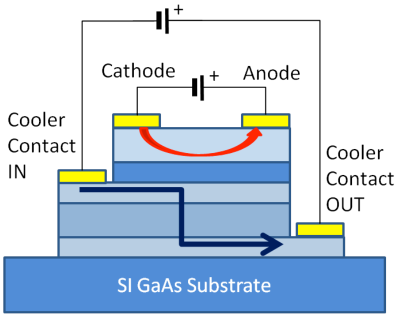

Figure 1. A schematical layout of integrated planar Gunn diode and micro cooler on GaAs substrate.

B. Device Layer Structur & Fabrication

Molecular beam epitaxy was used to grow layers on a 620 µm thick semi-insulating GaAs substrate. A 0.5 µm GaAs

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buffer layer was grown first on the substrate followed by a 300nm n-GaAs lower contact layer doped at 4×10^{18} cm^{-3}, 50nm graded aluminium gallium arsenide ($Al_{0-0.10}Ga_{0-0.90}As$), 100 periods of a $Al_{0.10}Ga_{0.90}As$-$Al_{0.20}Ga_{0.80}As$ super-lattice (totaling 2μm and maintain doping in supper-lattice and graded layer at 2×10^{18} cm^{-3}), 50nm graded ($Al_{0.10-0}Ga_{0.90-0}As$), and 300nm n-GaAs top contact layer. The super-lattice reduces phonon transport, providing a thermal barrier between the hot bottom contact layer and the cold top contact layer. A further 5 µm un-doped GaAs separation layer was grown on the top contact layer of micro-cooler layers. It is followed by the active part of the Gunn device consisted of the channel made of 50 nm un-doped GaAs t sandwiched by a 20 nm double δ-doped $Al_{0.23}Ga_{0.77}As$ layers. 15 nm of highly doped GaAs was grown on top of the $Al_{0.23}Ga_{0.77}As$ barrier layer to avoid oxidation. Finally, a 100 nm GaAs cap layer doped at 4×10^{18} cm^{-3} was grown for Gunn diode contacts. Figure 2 shows the epitaxial layer structure of the integrated Gunn and micro-cooler. The fabrication of the integrated devices starts with the planar Gunn device and the fabrication process is already described elsewhere [1]. The micro-cooler structure is defined by mesa etching, which enables a large number of different cooler geometries to be fabricated, as well as TLM test cells for measuring the contact specific resistance. The measured specific resistance of the ohmic contacts was $5\times10^{-6}\Omega cm^2$. The measured total resistance of a cooler, with an area of 20,000μm^2, was approximately 1Ω

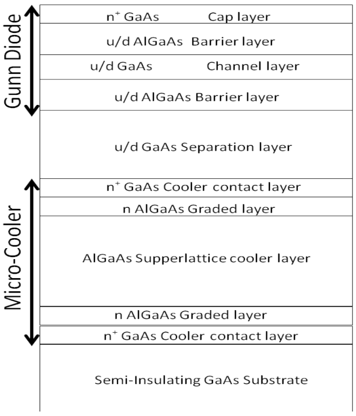

Figure 2. Layer structure of the integrated Gunn and micro-cooler.

III. RESULTS AND DISCUSSION

The fabricated coolers were measured on wafer by applying DC bias using micro-probes. To minimise the effect of probe heating at the top (cooled) contact, it was wire bonded to a metallised probe pad. The temperature difference between the hot and cold contacts is expected to be small therefore accurate temperature measurements are required. The contacts were monitored respectively, over a range of bias conditions, using high emissivity micro-particles imaged by infra-red (IR) thermal microscopy [5]. This enabled more accurate temperature measurements to be made than is possible using conventional IR measurements. The micro-cooler can be represented by the equation:

$$\frac{\Delta T}{R_{th}} = Q - I^2 R$$

where $\Delta T = T_c - T_h$ the difference in temperature between the hot (T_h) and the cold (T_c) contacts, I^2R is the ohmic dissipation in the cooler (R is the resistance of the top contact and half of the bulk internal resistances of the cooler), R_{th} is the thermal impedance of the cooler and Q is the cooling power. $Q=IT_cS_n$, where S_n is equivalent to the Seebeck coefficient. The equation can be re-arranged as

$$\frac{I^2}{\Delta T} = \frac{S_n T_c}{R} \cdot \frac{I}{\Delta T} - \frac{1}{RR_{th}}$$

Figure 3 shows the measured cooling of ~0.5°C at an ambient of 125°C and internal heating (I^2R) depending upon the current direction in the micro-cooler.

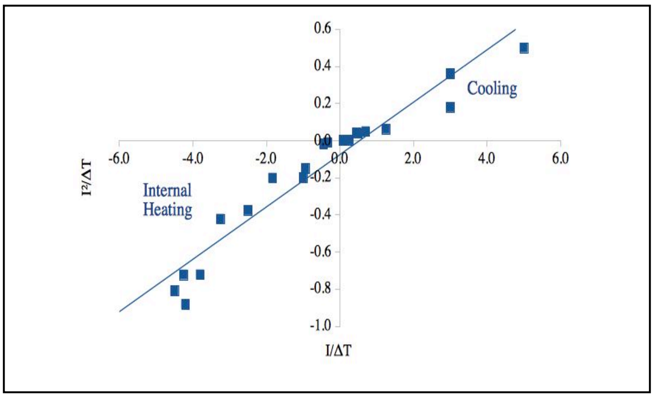

Figure 3. Measured results of micro cooler on GaAs substrate

IV. CONCLUSIONS

The paper presents the the design of an integrated micro-cooler with planar Gunn diode. The fabrication of an integrated micro-cooler with the planar Gunn diode is described and the characterization of the micro-cooler.Initial experimental results have shown 0.5Cofcooling at the top contact surface of the micro cooler.

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