Waveguide HBT electroabsorption modulators: devices and circuits

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Abstract

We show the monolithic integration of HBT and EAM which are merged to a combined device able to operate as an electronic and optical component (HBT-EAM) simultaneously. Comparison to a pure EAM made from the same InP-based layer stack gives an improved optical modulation contrast up to 20GHz. To demonstrate the concept a differential amplifier is built which results in a voltage gain of 8 at 2.55GHz, limited mainly due to a load resistor of 500Ω. To improve optical modulation an InGaAlAs-base is realized to give better contrast up to 10dB, while the DC current gain is at 3.5 and has to be optimized.

I. Introduction

The use of III/V-semiconductors enables combined electronic and optical devices, which are usually fabricated separately. One way for monolithic integration is to stack the layer structures of the devices on top of each other, resulting in individual devices, which however, have to be processed sequentially. In different approaches, two devices have been merged to reuse layers and to simplify processing. Shaw et. al. [1] e.g. used a heterojunction bipolar transistor (HBT) in combination with an optical switch employing refractive index changes for modulation. For GaAs-based HBTs Okada et al. [2] used the base region as a carrier-injected optical intensity modulator.

The following work focuses on the combination of HBTs and electroabsorption waveguide modulators (EAMs) by merging a modulator for 1.55μm wavelength into the layer stack of the HBT. In our InP-based approach we insert the waveguide into the collector region and use the electric field for band gap changes in the guide material for modulation (Franz-Keldysh effect, FKE) [3]. The resulting layer stack (Fig. 1) enables a new type of merged device (HBT-EAM), which corresponds to a modulator with an integrated amplifier and the demands to a driver circuit are reduced. Circuits developed are an opto-electronic differential amplifier among others. The circuits fabricated until now base on the layer structure shown in Fig. 1 a), where the collector of the HBT-EAMs contains the guide and the upper cladding. However, this results in a thick collector and therefore the electric field and the modulation inside the guide is weakened. As a remedy the upper cladding can be shifted into the emitter, i.e. the emitter is reused as a cladding layer as shown in Fig. 1 b). For this approach a transparent base layer has to be used.

II. Fabrication

Both types of layers according to Fig. 1 were realized. The layer structures were grown on InP-wafers with LP-

![Fig. 1. a) HBT-EAM with collector as upper cladding, b) new layer-stack with upper cladding moved into the emitter. This reduces collector-thickness and the electric field in the guide/collector increases.](image_url)

![Fig. 2. Circuit-schematic of the differential amplifier with ohmic current source. The EAMs are modulated in accordance to V_{CB}.](image_url)
MOVPE using alternative non-gaseous precursors. Both types of base layers were deposited at 500°C only to yield high carbon doping. Concerning the InGaAlAs layer a characterization by x-ray and photoluminescence measurements resulted in an Al-content around 0.15 suited to get low absorption at 1.55 μm wavelength. Technological realization employs a four mesa process to define, additionally to the known HBT-mesa, a passive waveguide besides the emitter, base and sub-collector mesa. Processing was done using optical lithography, conventional wet-chemical etching and metallisation steps.

To demonstrate the capability of monolithic integration of HBT-EAMs several simple circuits were designed employing the layer structure according to Fig. 1 a) (InGaAs-base). Common-emitter circuits using a HBT-EAM combined with on-wafer load resistances are realized in a first step. For comparison pure EAMs are also formed during the same process.

Fig. 2 shows the circuit-schematic of a differential amplifier with two HBT EAMs. The complete circuit layout is displayed in Fig. 3. The infrared laser light is fed into the passive waveguide on the left and split into two parts propagating to the right. Each branch contains an electrically controlled HBT-EAM which modulates the passing light simultaneously. Results are discussed in part III.

However, as mentioned before because of the thick collector the electric field is weakened. To improve the optical contrast in the devices and circuits the electric field in the guide has to be increased, which can be achieved by the layer stack according to Fig 1 b) where the upper cladding is moved into the emitter, therefore demanding a transparent base. This can be realized by adding aluminum into the InGaAs-As-base. From this layer structure HBT-EAMs were fabricated, too. Fig. 4 shows a SEM picture of a HBT EAM with a distinct emitter/base contact layout, where the emitter contact has a width corresponding to the width of the waveguide.

III. Results and Discussion

Fig. 5. Comparison of HBT-EAM with EAM from the same wafer (c.f. Fig. 1 a). The inset shows the HBT-EAM in common-emitter configuration with on-wafer load resistance $R$.

First a HBT-EAM is compared with an EAM made from the same epitaxial layer with InGaAs-base (c.f. Fig. 1 a). Fig. 5 plots the relative optical modulation from both devices versus frequency. Optical measurements were performed with a tunable laser source connected to the HBT-EAM and EAM, respectively, by a tapered single-mode fiber. A cleaved single-mode fiber is used to pick up the optical output. Electrical connections are made by coplanar probes to supply the RF-signal and the DC part via bias-tees. The active regions of the devices are always 50 μm long and the passive waveguide made from semiconductor material around 400 - 500 μm, depending on cleaving. The HBT-EAM constitute a common-emitter circuit with an on-wafer load resistor $R = 1000 \Omega$ to result in base-collector voltage swings which simultaneously modulate the built-in EAM. As can be seen in Fig. 5 the relative optical modulation of the HBT-EAM is higher than that of the pure EAM up to 20 GHz at the same electric input power $P_{in} = 0.05 mW$, demonstrating the gain of the built in HBT. However, the cutoff frequency is reduced due to the value of the load resistor used in the collector branch.

From the same layer stack differential amplifiers were also fabricated (see Fig. 2 and 3). First the electrical properties of the circuits were investigated. Fig. 4 plots the time-domain measurement of one electrical output port recorded with a sampling oscilloscope. The voltage gain is 8 at 2.55 GHz ($f_t$ and $f_{max}$ of the HBT-EAMs...
Fig. 6. Time-domain measurement of the electric output of the diff. amp (data was corrected in amplitude due to 50Ω environment). The inset shows pictures taken with an IR-camera looking at the optical output. Circuits based on a layer structure shown in Fig. 1 a). Active device length is 50µm.

around 250GHz). The inset displays pictures taken with an IR-camera showing the optical output under two extreme DC-conditions switching light between the two branches. Additionally the circuit wiring was extended to result in a RS flip-flop. This combines optical and electrical switching with latching the desired state (not shown here).

The circuits have a potential to be controlled also optically at a wavelength near or at the wavelength of the optical output. This could be achieved e.g. by feeding the controlling light to the HBT-EAM by a separate waveguide to be absorbed in the InGaAs base.

The following results are achieved on the basis of layer stack according to Fig. 1 b. Fig. 7 plots a common-emitter characteristic of a HBT with InGaAlAs-base layer. Current driving capability is approximately 4mA and breakdown voltage is above 8V, showing the compatibility with EAMs. The current gain however is about 3.5. Fig. 8 shows the modulation contrast of a HBT-EAM operated as EAM (i.e. modulating directly

$V_{bc}$ and therefore not relying on current gain) for the wavelength range 1570nm – 1580nm. The contrast reaches up to 13dB for a voltage swing of 8V and typical values around 10dB are available at operation wavelengths.

Because of the thinner collector the electric field available in the guide is increased. This demonstrates the possibility to get the same contrast at lower voltage swings and would enable simpler driver circuitry and improved speed. A problem so far is the reduced current gain. On one hand the Al-content facilitates incorporation of carbon to get higher doping levels and was exploited in [3]. But on the other hand the addition of $2–3%$ Al resulted in a reduction of DC current gain from a few hundred to 40. The reason for this degradation is a reduced valence band discontinuity to the InP-emitter therefore weakening the wide gap emitter effect. In addition, minority carrier lifetime is probably reduced due to impairment of crystal quality by incorporation of Al and impurities. First experiments, reducing base doping and increasing emitter doping, resulted in a current gain of 3.5 at an Al-content of 0.15. However other groups showed a higher gain with even more Al-content [3], suggesting further improvement should be possible and optimization is in progress. To use the higher available modulation contrast, the circuit layouts will be adopted as a next step to be consistent with the InGaAlAs-base structure.

IV. Conclusions

In summary we demonstrated the development of a merged HBT-EAM device. Several circuits employing this component were fabricated and monolithic opto electronic integration was demonstrated. Several points still need optimization, especially for better modulation, the current gain of InGaAlAs-base HBTs must be increased.

Fig. 7. Common-emitter characteristic of a HBT with InGaAlAs-base. Breakdown is over 8V, however current gain is at 3.5.

Fig. 8. Modulation contrast of a HBT-EAM used as an EAM (directly modulated at $V_{bc}$). The device with the new InGaAlAs-base shows higher optical modulation contrast due to the increased electric field in the collector region.
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References