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Novel Detectors and Lasers for Telecommunications

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Abstract

For the most part the field of optoelectronics has been dominated by the pn junction for both detector and laser applications. This domination will probably hold true for laser applications for many more years although the simple forward biased junction may be challenged by other novel approaches as increased complexity is required such as multi-wavelength emission, wavelength conversion, and Thz operation.

The first real novel use of the pn junction was developed by Balkan et al [1]. Their HELLISH device paved the way for novel approaches in the use of the pn junction. In this paper I shall introduce another novel use of the pn junction for light emission. Monte Carlo and Drift Diffusion modelling of the device will be presented as will our first experimental results. The applications of the device in telecommunications will be outlined which include multi-wavelength lasers and wavelength converters. In the field of detectors the pn junction has now a number of rivals. The main contenders are the MSM photodetector, the BG-MSM photodetector and the Low-Temperature (LT) family of MSM detectors. A brief overview of these devices will be given along with our experimental results on the BG-MSM device.

1. Introduction

The humble pn junction is extremely versatile. It has been used as part of many electronic circuits as a diode. In the field of optoelectronics it is truly the king of devices. It is fundamental to all semiconductor lasers and is greatly used as the basis for most detectors. This comes about from the basic underlying diode action. Biased in one way (forward) the pn junction brings together, in a controlled manner, two large populations of electrons and holes. In a direct gap semiconductor this leads to large recombination of electrons and holes with the consequence of band-gap light emission. The light emission can either be in-coherent as in the case of a simple light emitting diode (LED) or coherent as in the case of a semiconductor laser. Applying the bias in the opposite direction (reverse) acts to increase the depletion layer and separate the two large populations of electrons and holes by a region in which an electric field exists. The strength of the electric field depends on the magnitude of the applied bias. In this configuration there is only an extremely small current flowing until a sufficient bias is applied to invoke impact ionisation and eventual breakdown. At lower applied biases the device can be operated as a photodiode as long as the light that falls on the detector has a wavelength sufficient to excite electrons from the valence to the conduction band. This is all very well documented and until recently very few other devices have been considered to challenge the role of the pn junction in the emitter/detector realm of optoelectronics. The pn junction in both the modes of operation I have outlined here has to be fabricated as a non-planar device as the layers of p-type and n-type material are normally grown one on top of each other. This non planarity makes the device more complex to fabricate than planar devices. Also as the device has a clear asymmetry with regards to the biasing of the device care must be taken when operating it. It is common for a laser to be fabricated such that reverse biasing the device can cause damage. Similarily damage can be caused by forward biasing a photodiode. Planar light emitters and detectors that have polarity independent operation would be a great advantage as long as their performance was similar or better than the standard pn junction based devices.

Regarding light emitters one of the first examples of such a device is the HELLISH light emitter/laser. This device is dealt with in detail in another article in this journal [2] and so We will not go into great detail about it. It is sufficient to state that it is essentially a planar device which has two contacts which are bias independent. The device is based on a pn junction but the operation is entirely different. It relies on a hot electron/hole effect to drive electrons and holes together, thereby stimulating recombination and light emission. It is simple to construct. In its simplest form it requires only the surface diffusion of two metal contacts. In this paper we will discuss in detail our development of a novel light emitter which is a Hot Electron Barrier Light Emitter (HEBLE). This device is also based on a pn junction and also operates through a hot electron effect as the name implies. It is not planar however and it requires three contacts, two to the n-type layer and one to the p-type layer. Its main claim to novelty is in the way in which the electron and hole population are brought together. Essentially, as will be discussed in more detail in the next sections, the device is designed to place the hole population in the active region prior to turning on the device. The action of turning on the device uses electron heating to pump the electron into the active region. Although the device is not planar any modulation of the device is achieved through the two planar contacts made to the n-type layer. The challenge to the humble pn photodiode in the realm of detection is greater. The non-planar nature of the photodiode is a limiting factor in its potential bandwidth which is becoming of increasing importance in the field of telecommunications. This was realised some time ago and much work was done on the development of the metal-semiconductor-metal (MSM) photodetector [3]. The MSM photodetector requires only a simple piece of intrinsic semiconductor material onto which are deposited two metal contacts which form Schottky contacts. The device is completely symmetric with regards to the contacts and therefore does not depend on the polarity of the applied bias. The bandwidth of the device simply depends on the spacing between the two contacts. The closer the contact spacing the higher the bandwidth. The development of interdigitating contacts has pushed the range of the MSM photodetector into the THz regime [4]. Recent developments of short recombination time materials, commonly known as "low temperature grown" or LT materials has also shown THz performance [4,5]. All MSM photodetectors, with the exception of LT-MSM photodetectors, operate in what is known as "the transit time limited regime". In other words the speed of response of the device depends on the transit time of the electrons and holes in the device. This is why the shorter distance between contacts leads to a greater bandwidth. In most cases the holes are considerably slower than the electrons and therefore the device is limited by the speed of the holes. This was recognised by Greger et al [6] and by Vickers et al [7] who simultaneously developed the Back Gated MSM (BG-MSM). This device is a hybridization of an MSM photodetector and a p-i-n photodiode, which is a variation on the simple pn photodiode. The device, as will be discussed later, has three contacts. Two of the contacts are planar, on the surface of the device, and act as the photodetector contacts. The third contact to the p-type material, acts as a sink for holes, removing them from the photodetector signal and hence improving the device response speed. In the following sections the details of our investigations into the two devices we have been developing (the HEBLE and the BG-MSM) will be discussed.

2. The HEBLE Device.

2.1 The Basic Device Design

Our initial design was based on a pin structure and is shown in the figure below. From this sketch one can see that the difference between this device and an ordinary pin diode structure is the barrier created at the n-i interface.

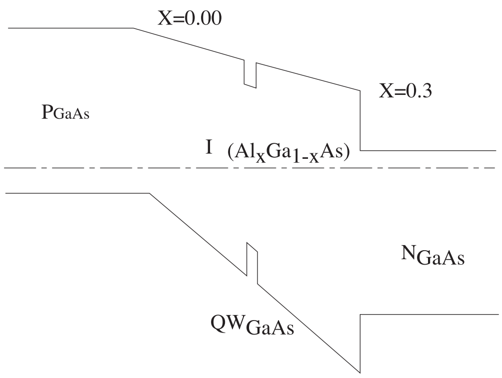

Figure 1. A schematic of the original HEBLE design

This barrier effectively prevents the diode from turning on as it prevents the diffusion of electrons into the intrinsic region which would happen in a normal diode under forward bias conditions. In this device, under forward bias, only holes diffuse into the intrinsic region and are captured by the quantum well. Electrons are driven into the active region by a heating field applied through two contacts diffused into the n-type layer. The heating gives the electrons sufficient energy to surmount the barrier. These electrons drift or diffuse, depending on the strength of the applied bias, across the intrinsic region and are captured by the quantum well where they can recombine with the holes.

2.2 Device Modelling

The structure above was determined after undertaking modelling using a Monte-Carlo code. The modelling was carried out at a fixed forward bias of 2.0V for different potential band offsets, (achieved by varying the alloy grading in the intrinsic region) at the n-i heterointerface. The test structure is shown in figure 2. The results of our initial modelling using a Monte Carlo code has been reported elsewhere [8]. Essentially this work allowed us to optimise the height of the barrier at the n-i interface. It was found in that work that a band edge offset of 0.19eV would be the optimum. Any lower and electrons would leak into the intrinsic region without requiring heating and any higher and the field required to heat the electrons would be too large. Subsequent to this original work we have undertaken modelling work using a two dimensional model incorporating the drift diffusion equations with self consistent numerical solutions of the Poisson and Schrodinger equations. The details of this work will be published shortly but here we simply give the results of the simulation for the original device (Figure 3)

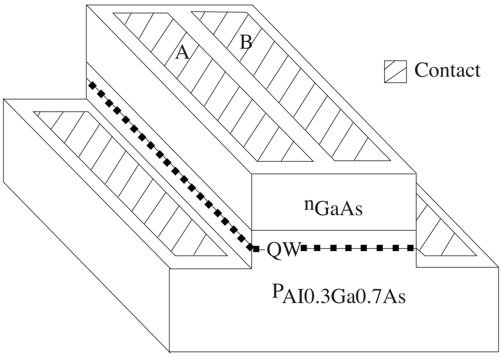

Figure 2. A The test device

and for a simplified device (Figure 4) which we arrived at after running the simulator for various variations of the device parameters attempting at each variation to optimise the device. Optimisation was defined as maximising the number of holes in the quantum well for the minimum applied forward bias whilst minimising the number of electrons in the quantum well.

2.3 Experimental Results

So far we have only undertaken experimental work on the original device as shown in figure 1 using the test device shown in figure 2. We have made a number of devices and taken IV and LI characteristics associated with applying bias to the two top contacts as a function of the forward bias applied to the bottom (p-type) contact. In order to achieve high heating fields and avoid heating the sample we have applied the bias to the two top contacts in the form of pulses with a low duty cycle. A typical set of LI curves are shown in figure 5. As can be seen clearly from these results the light is only emitted when the heating field reaches a value of around 4.5kV/cm and only when the device is forward biased in this example to 0.8V.

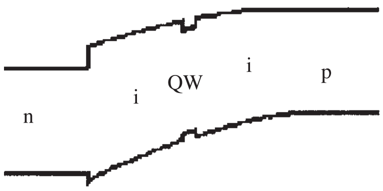

Figure 3. The simulation of the original p-i-n device.

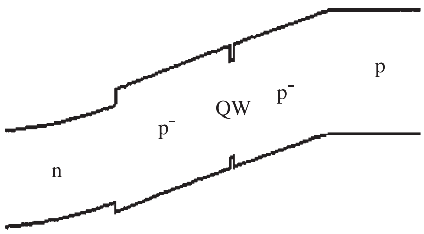

Figure 4. The simulation of the modified pn device.

We are currently finalising the work on the modified structure (Figure 4) and anticipate an increase in the light emission and a reduction of the required heating field.

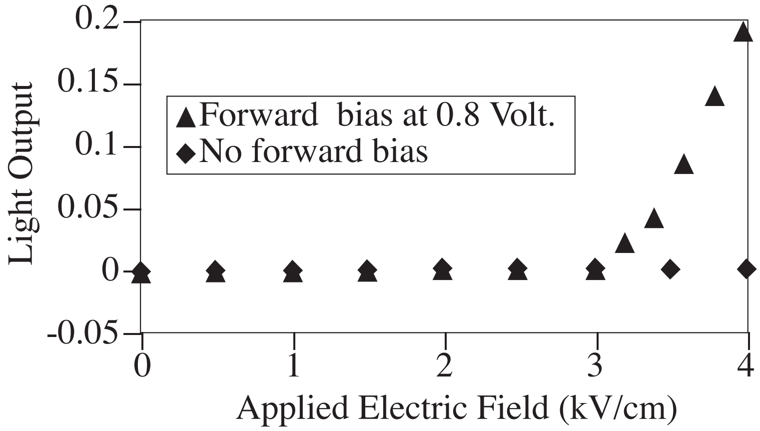

Figure 5. Light output as a function of the applied electric field

3. The BG-MSM Device

3.1 The Basic Device Design

Our basic device is based on a nip structure unlike that of Greger et al [6] which was based on a "ip" structure. The basic structure is shown below.

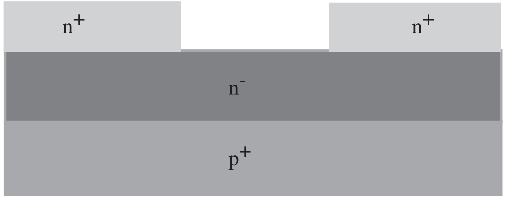

Figure 6. Light output as a function of the applied electric field

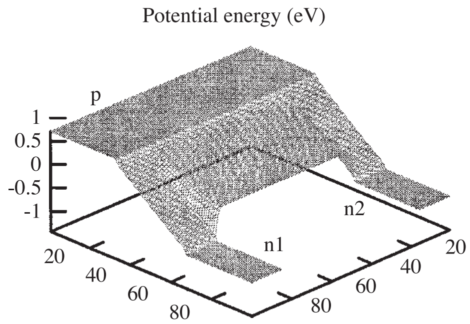

Figure 7. The potential energy profile in equilibrium

Two top metal contacts are made to the two n+ regions and it is through these two contacts that the photocurrent signal flows. A third metal contact is made to the bottom p+ region. This is the back gating contact which is the "hole extractor".

3.2 Device Modelling

We have constructed a two dimensional drift diffusion model with a self consistent Poisson solver in order to model the equilibrium and steady state properties of the device. A full presentation of this will be given in a later publication. Here we simple produce the results of the model for the case when the device is in equilibrium and for the case when 5V is applied between the two top contacts.

3.3 Experimental Results

The results for our BG-MSM devices can be summarised with a single figure for the case of a 10mm gap device with 10V applied across the two top contacts and with 11mW of optical power from a 1ps 500nm laser pulse focused onto the device. Figure 9 below is the relevant figure and it shows the full width at half maximum (FWHM) of the detectors response as a function of the voltage applied to the back gated contact.

From this figure it can be seen that when the back gating contact is "floating", in other words no electrical contact is made, the response width is around 300ps. When the back gating contact is connected to the circuit but no voltage is applied the response drops to around 245ps. A further reduction in width to approximately 230ps is achieved by the application of 8V to the back gated contact. The overall conclusion is therefore that the mear "earthing" of the back gating contact is sufficient to extract the hole current and produce an 18% reduction in the device response width.

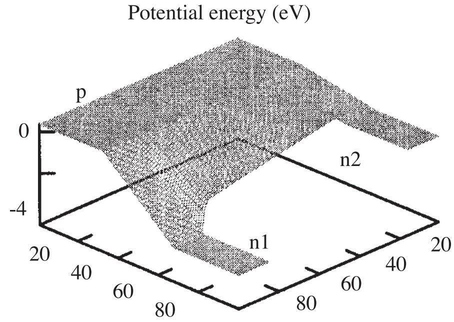

Figure 8. The potential energy profile with 5V applied across the two top contacts.

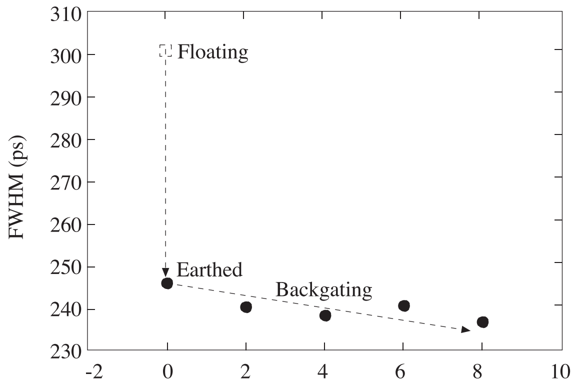

Figure 9. FWHM of the response as a function of back gating voltage

4. Conclusions

In conclusion we have outlined the current status of novel devices for light emission and detection. The HEBLE light emitter is in its early stages of development but could prove useful in certain areas such as multiple wavelength emission and wavelength conversion. In a future publication we shall be outlining our new plans for the development of a wavelength converter based on HEBLE, early ideas of which were presented in our initial paper on this work [8]. With regards to novel photodetectors we believe that there will be use for BG-MSM detectors as they will always be able to improve the response speed of an MSM detector and MSM detectors will no doubt overtake the use of pin devices in the area of THz communication systems.

References

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