Chapter VI
Conclusions

The purpose of this thesis is to investigate the nonlinearities (XAM and XPM) of EAM with Al-containing material in the MQW and apply them into all-optical processing, typically wavelength conversion and all-optical switching. Therefore, four main parts are included in this thesis: realization of the growth and monolithic integration of this special EAM by MOVPE, characterization of nonlinearities in a single EAM, a novel wavelength converter and a novel all-optical switching using the XPM in the EAM.

In **Chapter II**, the growth of the InGaAlAs MQW was firstly realized in our lab by MOVPE. Compared to the growth by MBE, MOVPE has more difficulties in the growth of InGaAlAs because the growth takes place at higher temperature and high pressure. We succeeded in the prevention of the Zinc diffusion to the core layer by thick SCH layer with +0.1% compressive strain. Then we investigated the butt-joint technique by using ex-situ cleaning. As far as we are concerned, the butt-joint regrowth in the Al-containing materials remains a challenge in the word. The difficulties arise from several issues of this monolithic integration including the shadow effect, vertical alignment, Al oxidation and overgrowth. We tried several etchants and chose the citric acid as the best solution for achieving vertical profiles in the InGaAlAs core layer of EAM. An hybrid etching method was also proposed to avoid the undercut. This etching method starts with the ICP dry etching of most of the core layer, and then the wet etching of the remaining thin layer. SEM images confirmed that this hybrid etching was very effective to obtain almost vertical sidewall of the core layer while avoiding severe under. In order to suppress the overgrowth, the two-step regrowth technique was also applied. By combining the two-step regrowth and hybrid etching, we optimized the whole growth and fabrication process, and improved the monolithic integration of high quality featuring in perfect connection at the interface, flat surface on the top and low coupling loss of 0.21dB/facet.

The main target in **chapter III** is to investigate the nonlinearities in an EAM with InGaAlAs/InGaAlAs MQW. For this purpose, we firstly introduced the theoretic analysis of the

QW structure. From the simulation, we saw that the change of the carrier density determines the changes of the absorption coefficient and the refractive index, which indicate the effects of XAM and XPM. Then the fabrication of the EAM with InGaAlAs/InGaAlAs MQW grown by MOVPE is introduced. In the third part, we showed the measurement results of a single EAM. Attention was focused to the measurement of the XAM and XPM. According to the results, both XAM and XPM were clearly observed. For XAM, the shorter the wavelength of the pump light is, the more the absorption coefficient changes; the intensity of the XAM also increases with the increase of the reverse bias voltages. XPM had the similar dependence on wavelength, however, it weakens when the bias voltage increases. In the fabricated EAM, 2π phase shift was obtained when the input power was 9dBm including 7dB coupling loss. The measurement results match well with the simulation. In this way we have finished the basic work for the wavelength converter and all-optical switch in Chapter IV and V: the fabrication of the EAM and the confirmation of the nonlinearities in EAM.

In **chapter IV**, we firstly investigated the nonlinear polarization rotation (NPR) in EAM. The polarization rotation originated from the difference of the refractive change for TE mode and TM mode, and can be applied for all-optical processing. This phenomenon has been well studied in SOA, but as far as we are concerned, this is the first time to investigate this in EAM. Then a novel wavelength converter based on NPR was proposed and demonstrated both statically and dynamically. In the static measurement, extinction ratio was larger than 30dB for both upward conversion from 1550nm to 1555nm and downward conversion from 1560nm to 1555nm. The enlargement of the extinction ratio was also found, which indicated the potential optical signal regeneration capability of the novel wavelength converter. In the 10Gb/s wavelength conversion experiment, clear eye diagram was achieved. In order to find out the way for high-speed operation beyond 40Gb/s, an equivalent circuit for the EAM was introduced. The analysis showed that the RC constant limited the speed of EAM. For lump EAM, the doping conditions and quality of ohmic contact of the electrode had important influence on the series resistance. Higher speed operation could be achieved by optimizing the electrode size and fabrication process. Finally, the quantum well width and compressive strain were studied theoretically. Simulation showed that narrowing of the quantum well width with compressive strain can effectively reduce the input power.

In **chapter V**, we proposed a novel all-optical switch by using two EAMs on the arms in the MZ interferometer. The switch is fabricated on the substrate grown by two-step regrowth technique described in Chapter II. We optimized the fabrication process of the devices in both ridge and high mesa cases. Then both of these two devices were carefully measured. In the all-optical waveguide with high mesa, because the insertion loss is so large due to the sidewall roughness and doping in the passive region, no dynamic operation was carried out. However, the static measurement of the wavelength conversion shows primary evidence for the all-optical switching of the fabricated device. The measurement of the XPM in a single EAM shows that the EAM does work well as the phase modulator by XPM. Therefore, the improvement of the devices performance lies in the reduction of the insertion loss. For this purpose, then an all-optical switch with ridge structure was fabricated. The measurement of the loss in the whole device shows that the loss can be reduced by 20 dB even when the total length is longer than the high mesa structure. The dynamic all-optical switching of 2.5Gb/s has been measured. Though the converted signal is of very poor quality, it is an evidence for the availability of the all-optical switches. Further investigation was done on MMI and EAM by cutting them from the whole switch. Experiments showed that in the EAM, XPM was clearly observed. This means the poor converted signal does not come from the EAM. On the other hand, the measurement of the output power in a single MMI showed 4dB unbalance between two output ports, which meant maximum 12dB unbalance in the whole device. We believe this is the main reason for the small extinction ratio in the dynamic wavelength conversion. By optimizing the MMI, dynamic performance of the all-optical switch can be improved.

Generally, the nonlinearities in EAM with InGaAlAs/InGaAlAs MQW have been investigated theoretically and experimentally. This EAM shows strong nonlinearity that can be applied to all optical processing. As examples, a novel wavelength converter by using nonlinear polarization rotation and a novel monolithically integrated MZI-EAM all-optical switch have been proposed and realized. We believe that EAM featuring stronger nonlinearity than fiber and faster response than SOA will play an more and more role in the all-optical networks.

Chapter VII

More consideration

Generally, the XAM and XPM arise from the change of the carrier density. In our previous discussion, this change of carrier density is only caused by the photo-generated carrier. If some other means can be applied to manipulate the carrier density or sensibilize the index directly, more flexibility of the control of the absorption and refractive index can be achieved and higher nonlinearity can be expected.

1. Enhanced nonlinearity of EAM by using DFB

Motivation

XAM and XPM both work in saturation state, which requires large input power. If some grating structures which are much sensitive to the change of the refractive index can be applied to the EAM, the optical nonlinearity can be significantly enhanced. As the consequence, the input power can be dramatically reduced.

Structure

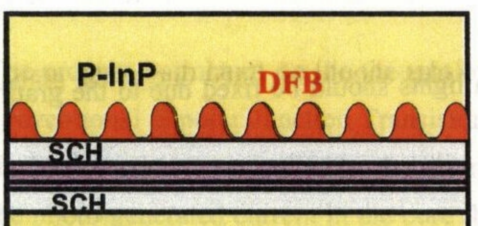


Fig.7.1 Schematic layer stack of DFB EAM

Application

1). Ultra wide range wavelength converter: 1310 to 1550

In the above scheme, the probe light does not rely on the band-filling effect, but on the grating, so the wavelength of the probe light can be far away from the absorption edge of the core layer. On the other side, the wavelength of the pump light is flexible only if it is close to the PL peak of the core layer. So

a. the insertion loss of the probe light can be very small due to the transparency of the core layer

b. the device suits for the ultra wide wavelength converter mostly from 1310 to 1550.

2). C band wavelength converter

Because the wavelength of the pump light should be close to the absorption edge, in the C-band, the loss of the probe light will become quite large. However, the nonlinearity of this device not uniquely depends on the saturation effect, but also the grating effect, the total nonlinearity will still be much larger than the conventional EAM, which means lower input power requirement and larger extinction ratio

More considerations

The insertion loss of the EAM is always the main issue in its application. However, the DFB can help to reduce it. In the case of C-band wavelength converter, we can make the probe light output from the same input side. In such case, in OFF state the DBR is set to be transparent, so the probe will be absorbed or output on the other side and no reflection at all. This means very lower OFF level. In ON state, we can inject the pump light and make the DBR work. Due to the reflection in the gratings, the equivalent propagation length will be much shorter.

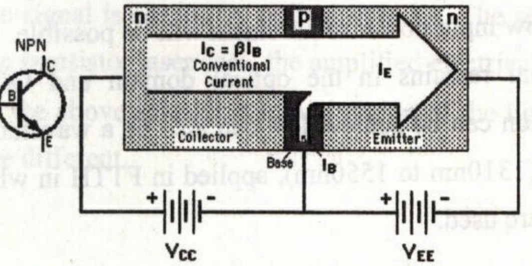
The main disadvantage is that one of the operation lights should be fixed due to the grating structure.

2. Optical laser transistor

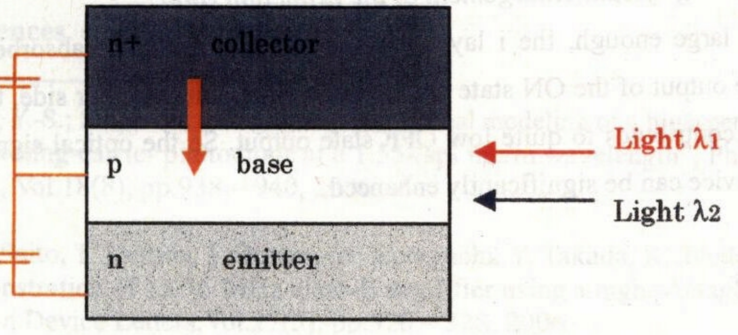
Motivation

XAM and XPM in EAM are both strongly depending on the photo-generated carrier density. If this density can be amplified by some other method, the requirement of the input optical power can be significantly reduced. The amplification of current can be easily realized by applying the similar method with bipolar junction transistor or field effect transistor (FET).

Structure



Electrical bipolar junction transistor (BJT)



EAM structure with transistor configuration

The i-region works as the core layer for optical lights, and the photo-generated carriers generated by light λ1 can be amplified by the forward bias in the i-n junction. Because the absorption of the light λ2 depends on the current in i region, the change of the absorption of this light will become much larger. If the amplification is large enough to generate the lasing, the device will become a semiconductor optical amplifier (SOA).

The proposed structure can be thought of the combination of the MQW EAM core layer and conventional Bipolar Junction Transistor (BJT). The difference is that, in conventional BJT, the base current is controlled by the external voltage, but in our case, the controlling current is the photo-generated current in the core (base) layer. So the emitter-base current is determined and amplified by the input light power. According to quantum confined Stark effect (QCSE), the absorption in the core layer will be greatly reduced, and large nonlinearity achieved.

Note that the core layer can also be i-type to reduce the absorption for specific application.

Application

1). High all optical nonlinear medium:

In semiconductor, the nonlinearity is always depending on the carrier density. If the carrier is only generated by optical power, the change of the susceptibility will be limited because the input power in the telecom is always small. By the electronic mean showing above, we can amplify the change of the carrier density, so the nonlinear performance can be greatly improved. In this way, optical devices with low input power requirement will be possible. Moreover, in the above scheme, the signal remains in the optical domain and O/E/O conversion is avoided and all optical operation can be achieved. It can also be a wavelength converter with quite wide conversion range (1310nm to 1550nm), applied in FTTH in which 1310nm, 1490nm and 1550nm wavelengths are used.

2). Regenerator with significant enlargement of the extinction ratio

If the amplification is large enough, the i layer may be transited from the absorber to the amplifier, by which the output of the ON state can be quite large. On the other side, the large insertion loss of EAM contributes to quite low OFF state output. So the optical signal noise ratio (OSNR) of this device can be significantly enhanced.

More considerations

Speed: The recovery time of the device depends on the drift of the carriers (both electron and hole). So similar to the SOA, the speed of the operation will be limited to several hundreds of ps. Note that, in electronics, many efforts have been made to improve the mobility of carrier and finally increase the operation speed; all the same methods can be applied to this device. For example, uni-travelling carrier (UTC) [1] can be realized by optimizing the diffusion distribution and the layer stacks, thus electron dominates the speed of the carrier; moreover, HEMT [2] is another option.

Amplification: As mentioned above, if the amplification is large enough, the EAM can be transited to SOA. This needs to be confirmed. However, even if it is not so large, and no amplification occurs at all, the nonlinearity can still be enhanced due to the amplified carrier density.

FET-like EAM: The above scheme is based on the transistor, in which current is used to amplify the photo-generated carrier intensity. Field effect can also be applied for this amplification, as well as the FET.

Compared to transistor laser [3]: In 2006, Prof. Feng in UIUC invent a novel device called transistor laser, from which both amplified electrical signal and lasing light are generated in the same thin layer, called "core layer" in optical term and "emitter" in electrical term. Our proposal seems quite similar with that. Especially, in both cases, the current is amplified for optical purpose. So both the transistor laser and the above device have similar structure and same way for large amplification. There are many differences. The first one is that for transistor laser, the signal fed into the device is electrical in the base, but in the above scheme, the signal is carried by optical light λ1. The second one is that they have different output. In the transistor laser case, the amplified electrical and optical laser outputs are the main concern. In the above scheme, the modulation of the light λ2 is the main concern. So the applications are different.

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