Development of Improved Photodiodes for Advanced LIGO

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1. Summary

We are seeking input from the LIGO Lab on the desired performance of photodiodes for the Advanced LIGO. We are particularly interested in the readout devices for the auxiliary length degrees of freedom. We believe that we can build devices which will be more in line with the Advanced LIGO requirements, and which can withstand larger peak power without damage than commercial devices.

These devices build on the rear-illuminated topology developed by David Jackrel at Stanford, but should be able to deliver higher speed devices.

The devices which David Jackrel grew have a larger than expected capacitance, which slows down the devices and makes them unsuitable for the for the RF auxiliary length sensing requirements. The “gap” which defines the capacitance for these PIN devices is the depleted region of the intrinsic (I) layer. Although the I layer in Jackrel’s devices was 2 microns thick, our measurements indicate that the depleted region is only 0.5 microns thick when running at the maximum safe reverse bias. We believe that this is due to the relatively high level of impurities ($10^{16}/\text{cm}^3$) in the I layer of the devices grown at Stanford.

Zhilong Rao has identified a commercial foundry which should be able to grow the required structure with a residual impurity level of approximately $10^{14}/\text{cm}^3$. This should lower the capacitance by a factor of 3 to 4. He has also identified some device processing modification which may lower the series resistance of the device.

We would like to use this commercial material to make some prototype devices. We will evaluate the devices to prove that they are better than anything LIGO has ever used. If successful, we will work with the Lab to fabricate enough for Advanced LIGO. In light of the central nature of these devices in the detector, we want to insure a tight coupling to LIGO lab in the development process, so these diodes can be used in Advanced LIGO.

2. What we propose to do

We propose to make some prototype devices which are 3 mm in diameter, that can handle 200 mA of photocurrent, have a capacitance of 200 pF, and have a series resistance of 10 to 15 ohms. These numbers are based on the demonstrated power handling and resistance of David Jackrel’s 3 mm devices, with 1/3 of the capacitance.

To develop these, we will buy (with our funds) 2 new wafers of the commercial diode material. Those wafers will be divided into segments. Each segment can then be processed into prototype devices and tested. The device fabrication steps are sketched in section 6. Interesting changes include the complete removal of the substrate, and the addition of a transparent front (ie towards the laser) contact to lower the series resistance. The transparent conductor will be a thin layer of cadmium tin oxide (CTO). That contact would mate with a traditional gold ring contact on the surface. We will also attach that ring to the external device leads with multiple wire-bonded leads to see if the wire bonds dominate the resistance. We will process several different sizes of devices for testing, probably 1.5 mm, 3 mm, and 5 mm diameters. We also note the possibility of increased power handling by using multiple devices in the way that Initial LIGO does, ie dividing the beam into several lower-power beams and putting those onto separate devices. By controlling the processing and procurement, we should be able to create a set of extremely well matched detectors on a common mount which may reduce the odd effects seen in Initial LIGO where the demodulated signals from the 4 ASQ devices are different.

The set of tests which need to be done on these devices is still in discussion. We plan to measure the R and C of the devices, the quantum efficiency, and the linearity and response to DC light levels. We plan to conduct damage testing, and should have at least 10 and perhaps 30 W of power at 1.064 microns for this. It would be useful to have RF response tests and spatial uniformity tests at DC and RF, but we may require assistance from the LIGO lab for this.

The majority of this development work is covered by Stanford's current NSF grant.

3. What we want from the LIGO Lab

We want to be sure that our efforts are directed at the needs of Advanced LIGO, and as such, we feel it is important that the LIGO lab provides several things for us.

1) The main requirements for the devices. We have quite a bit of flexibility in the design, particularly in the size of the devices, but there are some things we simply can not do. Hence, it is important to know what the requirements are for these devices before we proceed. Based on recent conversations with Rich Abbott and Rana Adhikari, we believe we have reasonable set of performance requirements for the devices. These are discussed below.

2) The ancillary requirements for the devices. In addition to the power handling and capacity of the diodes, there are many other things demanded from these devices, such as RF spatial uniformity, damage thresholds, and backscatter. We need to know these parameters as well. The most recent work on this that I know of was done by Mike Zucker for the main GW channel devices in 2000 (G000024-00).

3) Test plan. We need to develop a testing plan to make sure we learn everything we need with respect the various requirements. I expect that most of the testing will be done at Stanford.

4) Help with some of the tests. We can do many of the tests on these devices, but if the LIGO lab is already set up to conduct certain tests like RF uniformity, then help with those tests would be useful.

5) Quantities and timelines. We need to know how many devices LIGO will need, and when they are required. This is particularly important with regard to finding contract processing and packaging facilities.

6) LIGO contact. We feel it would be useful to have someone in the lab working with us on this project who understands Enhanced LIGO and Advanced LIGO, and has time to work with us and think about this topic.

4. Risks

The two largest risks we see are device biasing and quantity production.

Biasing: The diode properties are improved by reverse biasing the devices. The biasing provides 2 distinct advantages - lowering the capacitance and extending the linear response to higher power. The capacitance is lowered because the bias moves carriers from the intrinsic region of the device and makes the depletion region similar in size to the intrinsic region. This should not be a major concern with the new devices, because the intrinsic region of the new devices should have substantially fewer impurities. The other benefit of bias is to sweep out the photon-induced electron-hole pairs (the signal) and thereby minimize space-charge. This space-charge screens the external bias, and allows the signal pairs to recombine instead of generating electrical signal. This effect was the issue which limited the linear response of David's diodes. This is a particular concern, because the depletion region in the new devices is 3 times wider than the previous devices, so the imposed voltage must also be 3 times larger to create the same electric field across the depletion region. Reducing the impurities of the I layer may affect this scaling argument. It may be that reducing the impurities increases the carrier lifetime or that it improves the charge mobility, so a full factor of 3 larger bias may not be required. However, the bias of the previous devices was limited by device breakdown, which is not a well understood process, and is, at least in part, affected by the processing of the devices. We hope that flowing photoresist around the device mesas will allow sufficient biasing for the devices to meet our goals. In short, there is a risk that the linear power handling of the devices may be limited by our ability to process the devices.

Quantity Production: While prototyping a few devices is an excellent student project, quantity production and packaging of several hundred is not. We need to explore the possibility of working with outside vendors to implement our processing. We might also be able to hire a Stanford technician by the hour to do this in our facilities, or to hire a student for a quarter. It is probably possible to get the packing done by a commercial concern, but this is also an area of concern.

5. Requirements

Recent conversations with Rana Adhikari and Rich Abbott have focused the design parameters to the following

<u>Quantum Efficiency</u>: Not a driving factor. The auxiliary light ports are expected to have plenty of light power. The important parameter is the detected photocurrent, not the quantum efficiency. This is in stark contrast with the main gravitational wave readout channel, or any channel which relies on detection of non-classical light states to achieve improved performance.

<u>Photocurrent:</u> The devices should be able to receive between 100 mA and 200 mA of photocurrent. It is also interesting to look at devices with higher power, but the present design of the Advanced LIGO interferometer assumes 100 mA devices, and is believed to have sufficient noise performance. The ability to detect higher power would simplify the servo loop design.

<u>Detection Frequency:</u> The device should be able to be tuned to up to either 50 MHz or 100 MHz. The goal for the Advanced LIGO detector is to have all the auxiliary length readouts be done at frequencies of less than 50 MHz, but as of Dec. 2006, the IFO design team was not confident that can be achieved.

Tuned Impedance: We will use the range of 10 to 20 nVrms/√Hz as the signal level we are trying to reach with the shot noise times the impedance. For 200 mA of current, this becomes 40 to 80 ohms. To reach this impedance, we will need to use a tuned circuit with an external tuning capacitor and inductor, similar the new GEO style.

Diode Series Resistance: The resistance should be kept small. We measure values of 10-15 ohms, and will use that range. We will try to make the resistance as small as possible with the new processing steps which have been identified. Smaller resistance improves the Q of the tuned impedance, which improves the performance of the readout circuit.

Diode capacitance: We will strive for a 3 mm device with a capacitance of 200 pF. This is about a factor of 3 smaller than the capacitance of the 3 mm device we have now (which is 580 pF at 10 V bias).

There are several variants on the new tuned readout scheme for Advanced LIGO. These all rely on an external tuning capacitor, C_t, as well as an external inductor, L, to turn the response to resonate at the readout frequency. The series tuned impedance for the new style readout is approximately

$$Z_{tuned} = 1 \Big/ \left(\omega_0^2 \cdot R_1 \cdot C_{pd} \cdot C_s\right)$$

where ω_0 is the detection frequency, R_1 is the total readout resistance, C_{pd} is the photodiode capacitance, and C_s is the series capacitance of the external tuning capacitor plus the photodiode, i.e. $C_s = C_{pd}*C_t/(C_{pd} + C_t)$.

To give a feel for the numbers, we present four cases in the table below. The detection frequency and the shot noise equivalent voltage noise (in blue) are parameters of the detection requirements. The photocurrent, diode capacitance, and series resistance (in green) are parameters of the devices. Given these parameters, one can calculate the necessary values of the tuned circuit (in purple) to see if they are reasonable.

Requirement range (easy), which has specifications for the current diodes, and the easy performance specifications for the detection circuit.

Requirement range (hard), which shows about how well we might be able to push the devices, and the difficult end of the electrical detection specifications.

Present diodes, high frequency, which shows the current devices with the difficult end of the performance requirements. It looks difficult to implement the detection circuit for this case.

Good diode, easy spec, which shows an improved device with the easier end of the performance requirements.

For each these cases, we compute the requirement on the tuned impedance, and the external devices required to meet these goals. We see that the first two cases seem plausible, requiring tuning capacitors of 15 to 20 pF, and reasonable inductors. However, using the present devices with the strict end of the requirement range requires tuning capacitors of 2.5 pF and 1 uH inductors, which does not seem so practical, as the stray capacitance and the resistance of the tuning inductor will surely present a challenge. On the other hand, if we can make a good device, and we end up on the easy side of the performance requirements, it should be quite easy to make a tuned readout which will work for Advanced LIGO. It is worth noting that even this most optimist case is not possible using the Initial LIGO readout scheme.

Parameter	Requirement range (easy)	Requirement range, hard	Present diode, high freq.	Good diode, easy spec.
Detection Freq.	50 MHz	100 MHz	100 MHz	50 MHz
Shot noise equiv voltage noise	10 nV/rtHz	20 nV/Hz	20 nV/rtHz	10 nV/rtHz
Photocurrent	100 mA	200 mA	100 mA	200 mA
Capacitance for 3mm device	600 pF	200 pF	600 pF	200 pF
Diode series resistance	15 ohm	10 ohm	15 ohm	10 ohm
Tuned Impedance (Vn/I_shot)	56 ohm	79 ohm	111 ohm	40 ohm
Cs, Series Capacitance	20 pF	16 pF	2.5 pF	128 pF
Ct, Tuned Capacitor	21 pF	17 pF	2.5 pF	357 pF
L, Tuned Inductor	503 nH	158 nH	1000 nH	79 nH

Table 1. Sample requirements for a tune RF photodiode readout circuit.

6. Structure and Processing of the Proposed Devices

The high capacitance in our previous devices is partly due to the narrow depletion width as a result of high background doping in the intrinsic layer. We propose a new epitaxy structure to reduce the capacitance. The proposed photodiode epitaxy structure mainly consists of 1um In0.52Al0.48As n+ layer, 2 um In0.53Ga0.47As intrinsic layer and 500 nm In0.52Al0.48As p+ layer.

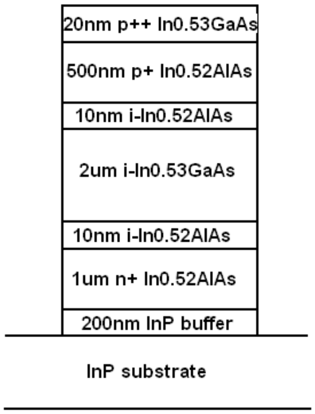

Figure 1: Epitaxy structure of the proposed new photodiode

We have found a vendor named IntelliEpi which can potentially provide the epitaxial growth with MBE for our proposed structure. This company claims to be able to achieve an ultralow background doping around 1e14 cm^{-3}, which is about an order of magnitude lower than that with typical MBE systems. This low background doping can ensure that the 2 um intrinsic layer can be completely depleted under a small reverse bias.

A schematic of the processing flow is shown below:

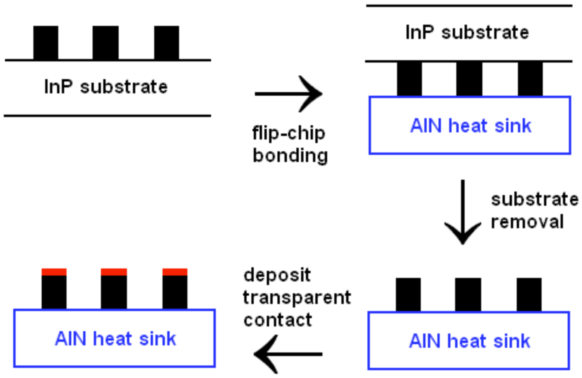

Figure 2: Processing flow for a photodiode array

Using a transparent contact such as cadmium tin oxide (CTO), we can significantly reduce the back-scattering of light signal and can even design the CTO thickness so that it also functions as an anti-reflection coating.

This processing is also clearly compatible with parallel device arrays.

7. R-C testing of the existing devices

We measured the R-C values of the GaInNAs photodiodes with 3 mm diameter. The schematics of the measurement circuit is shown below:

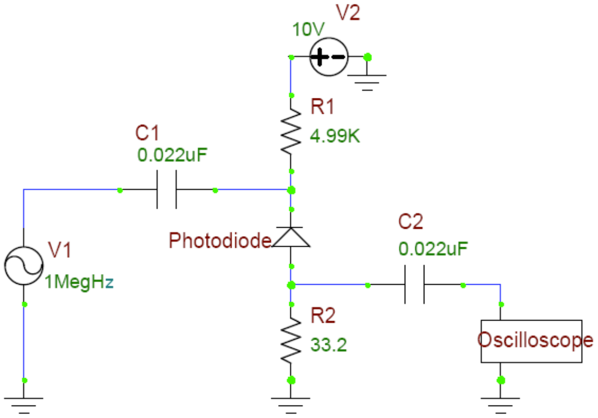

Figure 3: Schematic of the RC measurement circuit

We apply a reverse bias varying from 0 to 10 V on the photodiode. An AC signal with amplitude of about 200 mV and frequency of 1 MHz is sent through the photodiode.

The output signal is read out through an oscilloscope. The relation between the output and input signal is given by:

$$\frac{V_{out}}{V_{in}} = \frac{R_2}{R_2 + \frac{1}{j\omega C_1} + Z_d} = \frac{R_2}{R_2 + \frac{1}{j\omega C_1} + R_s + \frac{1}{j\omega C_d}}$$

where Z_d is the impedance of the photodiode, R_s and C_d are the serial resistance and junction capacitance of the photodiode respectively.

The serial resistance of the photodiodes is measured to be about 15 ohm. A typical capacitance vs. reverse bias curve is shown below:

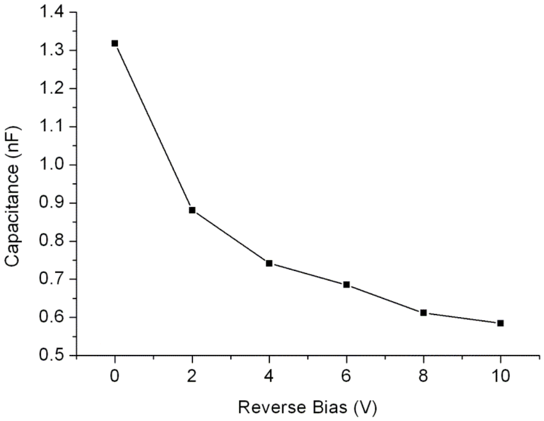

Figure 4: Capacitance vs. reverse bias voltage

At a reverse bias of 10 V, the capacitance is 0.58 nF, i.e. 580 pF. As we can see, the measured capacitance of our previous device would make this device very difficult to use for Advanced LIGO.