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INTEGRATED POWER AND DATA TRANSCEIVER DEVICES FOR POWER-BY-LIGHT SYSTEMS – A CONCEPT STUDY

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ABSTRACT: In optical power transmission systems photovoltaic cells are used as power converters for monochromatic light. In case of powering remote sensors, supplementary to the optical power link also bidirectional data transmission between the two sides of the optical link is required. It is appealing to integrate the functionalities of the optical power link as well as the data up- and downlink into one. In this work, different concepts on how this integration and combination of functionalities can be realized are explored and possible system and device architectures for integrated transceiver devices are discussed, including different examples of practical realizations based on advanced semiconductor fabrication techniques.

Keywords: III-V semiconductors, laser power converter, optical power transmission, optical communication

1 INTRODUCTION

Optical power transmission is an elegant way to power sensor electronics in demanding and challenging environments. Application examples for this technology can be found in various domains and are as diverse as structural health monitoring in wind turbines [1, 2], cortical neural sensing in brain implants [3], wireless powering for implantable sensing platforms [4], monitoring of high voltage power lines [5], optically powered video surveillance [6], submarine hydrophone and seismometer networks [7], passive optical networks [8]. Advantages of power-by-light technology, compared with conventional copper wiring, include inherent galvanic isolation, electromagnetic compatibility, magnetic resonance compatibility, lightning protection, explosion protection, and low weight. Central components of the system are a laser as light source and a photovoltaic laser power converter [9]. Typically the optical power is transmitted via an optical fiber. However, even wireless power transmission is feasible.

Since optical power transmission is often used to supply sensor electronics, in addition to the power link bidirectional data transmission between base station and remote sensor is desirable [1-8, 10-16]. To realize a purely optical power and data link, multiplexing[1] of three functionalities at both respective sides (base and remote) are required, namely power link transmitter and receiver (P-Tx, P-Rx), data downlink transmitter and receiver (Dd-Tx, Dd-Rx), and data uplink receiver and transmitter (Du-Rx, Du-Tx), located at base station and remote appliance, respectively (compare Figure 1). P-Rx is typically a photovoltaic (PV) laser power converter. Depending on the required power level and system architecture various laser types can be used as P-Tx, laser diodes are very common; furthermore light emitting diodes (LED) are possible. For Dd-Rx and Du-Rx photo diodes are used (PIN diodes, avalanche diodes). For Dd-Tx and Du-Tx both LEDs and vertical-cavity surface-emitting lasers (VCSEL) are commonly used.

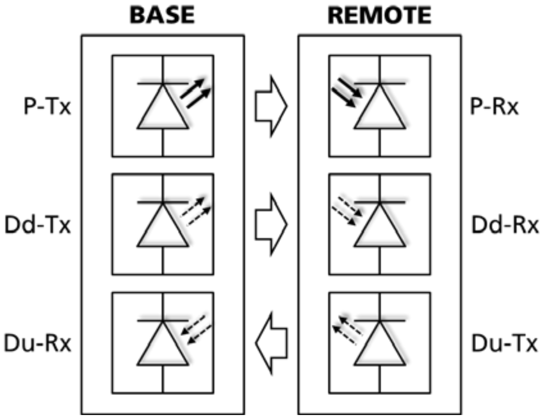

Figure 1: Schematic of the required functionalities (transmitter Tx, receiver Rx) at base station and remote appliance for power link (P-), data downlink (Dd-), and data uplink (Du-). Thick and dashed arrows indicate the power beam and data stream, respectively.

This work explores different possibilities to realize these functionalities on system and device level, and practical ways to implement them are discussed. For implementation combinations of advanced semiconductor architectures and processing tools are considered, such as monolithic multi-junction stacking, bi-facial epitaxial growth, multi-segment lateral separation, mechanical stacking/device bonding, wafer bonding, or the use of quantum wells for bandgap engineering.

2 ARCHITECTURES FOR POWER+DATA

2.1 Space division multiplexing

A straightforward solution for the integration of functionalities is space division multiplexing (SDM). This means that one power link and two data links are realized in three independent channels, namely one optical link connects laser (P-Tx) and PV cell (P-Rx), and one is used respectively for data up- and downlink (Du-Tx/Dd-Tx: VCSEL/LED, Du-Rx/Dd-Rx: photo diode).

2.2 Wavelength division multiplexing

Especially for long transmission distances, it is

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[1] It is remarked that the term ‘multiplexing’ in this work is referring to the integration of power and up- and downstream data signals, and thus is used somewhat differently than in telecommunication.

beneficial to couple all channels into the same fiber. That way installation cost and weight related to the fiber itself can be reduced. This can be realized by applying common wavelength division multiplexing (WDM) techniques. That means that for the respective multiplexed transmitter devices different wavelength devices are used (with appropriate receivers), e.g. 830 nm for P-Tx with a GaAs based photovoltaic laser power converter as P-Rx, 1310 nm for data downlink (Dd-Tx, Dd-Rx), and 1550 nm for data uplink (Du-Tx, Du-Rx). Specifically for the bidirectional data link existing optical transceiver solutions can be applied.

2.3 Power beam as carrier for data uplink

To reduce power consumption on the remote side, the data uplink can be realized by taking part of the power beam and reflecting it in a controlled way for the data uplink. In other words, part of the power (down-)link is used as carrier for the data uplink. This can be implemented by the use of optical micro-electro-mechanical systems (MEMS) or micro-opto-electro-mechanical systems (MOEMS), such as optical switches or micro-mirror devices. Thereby, only a fraction of the power that would be required for a VCSEL or LED transmitter is needed to power the micro device. Using a mirror with only small reflectivity the data uplink can be realized continuously without compromising the power link. If a fully reflecting mirror is applied, the multiplexing between power downlink and data uplink can also be realized in the time domain (TDM), e.g. 95% of the time the power beam is directed down to the PV receiver and converted to electricity, and during 5% of the time the power beam is used for the data uplink by modulated back reflection. The back reflection can be coupled into a separate fiber (SDM) to be guided to a photo diode (Du-Rx) at the base station. It can also be coupled back into the fiber of the power downlink and e.g. an optical circulator can be used to direct the data uplink to the Du-Rx.

2.4 Amplitude modulation

An elegant way to integrate power and data downlink is using amplitude modulation, or more precisely adding a modulated signal (data downlink) to the DC power beam. That way, the data stream can be read off directly from the PV cell output by appropriate electronic circuitry, thus it combines P-Rx and Dd-Rx functionalities. This approach can further be combined with WDM. That way a fully optical transceiver with all three desired functionalities at each side can be realized.

3 INTEGRATED TRANSCEIVER DEVICES

3.1 PV cells as data receiver

High bandwidths photo diodes are typically thin p-n junction devices optimized for minimal RC time constants, i.e. maximal cutoff frequencies. On the contrary, PV laser power converters are comparatively thick devices optimized for full absorption of the impinging light; thus compromising response time. A device with the purpose of combining both functionalities, power and data reception (P-Rx, Dd-Rx), needs to be optimized for data rate and bandwidth as well as absorption and light-to-electricity conversion efficiency.

3.2 PV-LED transceivers

Since PV cells and LEDs are in principle the same devices, namely a p-n junction, PV cells used as P-Rx can also be used for data transmission Du-Tx by operation in forward bias, i.e. in electroluminescence mode. On the contrary, an LED as Du-Tx could in principle also be used as photovoltaic receiver Pd-Rx. The emission wavelength of a PV-LED device is determined by the bandgap of the emitting semiconductor material, in the case of a PV cell the absorber material. It is noted that the optimum operating point with respect to wavelength is typically some few tens of nm below the emission wavelength determined by the bandgap [17]. Thus, if this combination is applied e.g. at the remote side, the wavelength difference can be used by WDM techniques to direct the light on the base side with respect to P-Tx and Du-Rx.

3.3 PV-LED transceivers with quantum wells

An interesting idea building on the previous thought is to make use of a quantum well (QW) structure [18, 19]. Here the absorbance properties from the bulk material and performance of the PV under monochromatic light (e.g. in terms of spectral response and output voltage) are only marginally influenced; though, by tuning the QW properties the luminescence spectrum, i.e. the emission peak wavelength, can be tuned to a reasonable degree of freedom to photon energies well below the absorption edge of the bulk material. Consequently, P-Rx, Dd-Rx, and Du-Tx can be realized with a single device: By implementing amplitude modulation on the power link (see Sec. 2.4) power and data downlink are both realized using the bulk PV material as receiver (e.g. 808 nm to 850 nm range laser light for the downlink to a GaAs based device). The data uplink transmitter is realized by modulated forward biasing of the same device to generate the data signal from electroluminescence from the QW (e.g. ≥880 nm for the uplink emitted from GaInAs QW). At the base station wavelength division de-multiplexing can be used to direct the respective optical stream to Du-Rx.

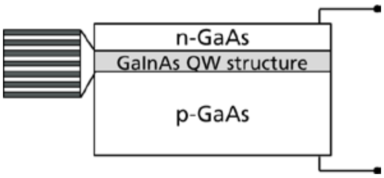

Figure 2: Schematic of a n/p-GaAs PV cell for absorption of e.g. 830 nm laser light (P-Rx+Dd-Rx) with integrated GaInAs quantum well structure for emission of the data upstream on a higher wavelength (e.g. 880 nm) as Du-Tx.

3.3 Vertical integration

By application of advanced semiconductor fabrication techniques for vertical integration, individual functionalities (i.e. LED, VCSEL, PIN photo diode, photovoltaic cell) can also be integrated into a combined device. This can be done monolithically by epitaxial growth of multi-junction devices, eventually added by appropriate etch stop layers, tunnel diodes, absorber and lateral conduction layers, and Bragg reflectors (similar to e.g. monolithically integrated VCSEL-PIN transceivers for optical communication [20]). In the analogous fashion, wafer-bonding of separately grown structures can be applied for vertical integration, eventually combined with multi-junction growth. Moreover, bi-facial epitaxial growth techniques allow for realization of two devices with different functions on the two sides of a single wafer. That way e.g. a higher wavelength Du-Tx can be realized on the rear side of the P-Rx(+Dd-Rx) device. Finally, vertical integration can also be realized on device level by mechanical stacking of individual devices, or by direct device bonding.

Example device architectures are depicted in Figures 3 to 5 and detailed in the respective captions.

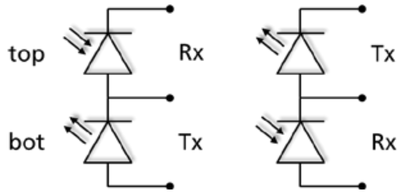

Figure 3: Schematic of an integrated transceiver which can be realized by monolithic growth (vertical stacking) and three terminal contact scheme, e.g. realized by partial selective etching of the top device. Using amplitude modulation Rx can be an integrated power and data downlink receiver. Light is assumed to come in and go out on the top of the figure. Thus, the top device layers must be transparent for the bottom device wavelength (lower bandgap material): $E_{g,bot} < E_{g,top}$. Alternatively, this scheme can also be realized by mechanical stacking of individual devices. Finally, in the same fashion the third functionality can be added to the stack.

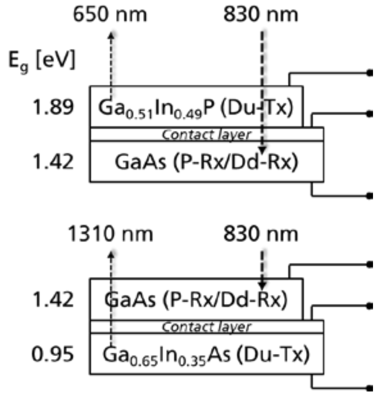

Figure 4: Two example realizations of the approach shown in Figure 2. *Top*: A $Ga_{0.51}In_{0.49}P$ based transmitter Du-Tx (650 nm) can be grown lattice-matched on top of a GaAs based receiver (P-Rx and Dd-Rx with amplitude modulation). The upper Du-Tx as well as the intermediate contact layer are transparent for the 830 nm range downlink beam. The transparent and conductive contact layer is implemented as common terminal for the upper junction's back and lower junction's top contact. It is accessed from the front side of the device. In addition, the bottom layer of the GaInP p-n junction can be of additional use to support lateral conduction and current distribution in the top layer of the GaAs PV cell p-n junction. *Bottom*: A $Ga_{0.65}In_{0.35}As$ based Du-Tx emits at 1310 nm (0.95 eV). Above the combined receiver P-Rx + Dd-Rx (amplitude modulation) is realized based on GaAs for an 830 nm range power and data downlink, which is transparent for the 1310 nm emission. The device can be realized by inverted growth techniques on a GaAs substrate, i.e. first the GaAs receiver is grown upside down, and afterwards the ternary GaInAs transmitter is grown based on a metamorphic approach with a step-graded buffer which can also additionally be used as intermediate lateral conduction and contact layer. The lower bandgap of the Du-Tx compared to the previous example has the advantage that it requires a lower driving voltage for the data uplink.

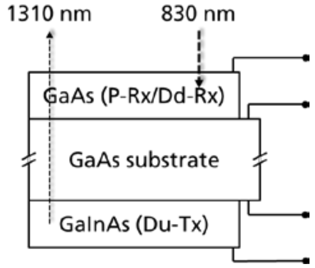

Figure 5: Example of a vertically integrated transceiver based on bi-facial growth. The P-Rx+Dd-Rx is realized as a GaAs based PV cell on a GaAs substrate, well matching a 830 nm modulated power and data downlink. The data uplink is transmitted by a GaInAs based Du-Tx on the rear side of the substrate, which emits at 1310 nm and consequently the substrate and the PV cell are transparent for the light of the data uplink. The transmitter can be realized e.g. as a VCSEL.

3.4 Lateral integration

Multi-segment device architectures (also known as monolithic interconnected modules, MIMs [21-23]) are well known for PV laser power converters [24-28]. The benefit of multi-segment PV converters is that due to the series connection higher output voltages can be delivered at device level – as strongly desirable for efficient power management for reliable power supply of sensor electronics at e.g. a constant voltage of 5 V DC. The multi-segment concept is based on epitaxial growth of the semiconductor structure on a semi-insulating substrate – as an alternative solution an appropriate blocking diode that suppresses current flow from the active layers to a conductive substrate could be implemented inside the structure. The active layers are laterally split into electrically separated segments by isolation trenches. Interconnection of the segments and/or contacting of individual segments (both +/- terminals) are realized on the front side by a combination of a structured dielectric and front side metallization.

Based on the multi-segment approach, all desired functionalities can be integrated into a single device, namely by using a single p-n junction structure as (multi-segment) PV laser power converter (P-Rx), in reverse bias as photo detector (Dd-Rx), and in forward bias as LED (Du-Tx). It is noted that the combination of PV cell (P-Rx) and LED (Du-Tx) has been proposed previously [29]. Figure 6 shows three examples as schematic drawings of how this approach could be realized.

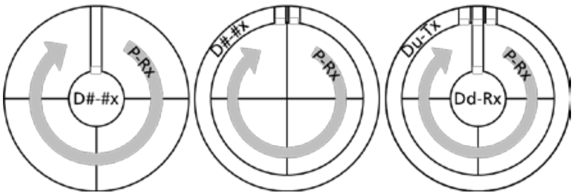

Figure 6: Schematic drawings of examples of a lateral integration of a data functionality into a multi-segment PV laser power converter (P-Rx); the gray arrow indicates the series connection of the PV segments to

increase the output voltage. The term “D#-#x” is used to indicate that the respective segments could be used for data transmission (Du-Tx) as well as reception (Dd-Rx), depending on usage (forward biasing LED mode or reverse biased photo detection), or even both multiplexed in the time domain (TDM). Electrical contacting (not shown here) can be realized outside the circular active area, respective conductive paths are sketched by white connections to the outside of the circle. *Left*: A central segment is used for the data link, whereas as an example four outer series connected segments are used for conversion of the power beam. *Middle*: The data segment is moved to the outer part of the active area. That way the usually high power in the center of the beam can be absorbed by the power receiver for electricity generation. Hence, this design is considered to be beneficial for power transmission, but might deteriorate signal-to-noise ratio of the data link. *Right*: Combination of the previous two with data transmitter in the outer region and data receiver in the center of the active area.

3.5 Areal splitting

Splitting of the device area can be beneficial, especially for multi-junction architectures. Here, e.g. upper junctions can be partly removed (by selective etching) to enable direct light exposure of lower layers. That way, the design rule of full transparency of the upper layers can be circumvented to gain more freedom in device design. Figure 7 shows an example of a 3-junction structure with partly removed layers.

In addition, devices of different can be integrated to still guarantee operational functionality of their individual purpose. E.g. a small sized VCSEL, LED or photo diode can be bonded onto a comparatively larger photovoltaic receiver. That way, the small sized device is fully functional, whereas the PV cells absorber area is only marginally diminished (compare Figure 8).

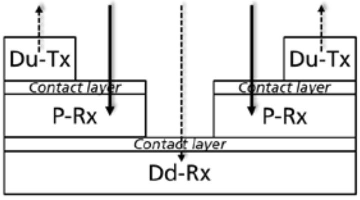

Figure 7: Example of a 3-junction device with partial removal of the upper junctions. That way, the upper layers do not need to be fully transparent to guarantee light impingement on the desired junction.

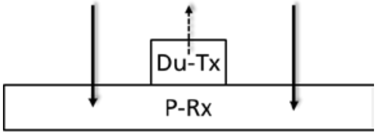

Figure 8: Example of a device bonding of e.g. a small sized VCSEL as Du-Tx bonded to a comparatively larger PV cell as P-Rx.

3.6. Combinations of different approaches

Obviously the concepts presented in the previous sections can also be combined with each other in different kind. As an example a multi-segment device for P-Rx and Dd-Rx as described in Sec. 3.4 can be combined with a Du-Tx realized on the rear side of the substrate by bi-facial growth. Another example is a multi-junction structure as shown in the bottom of Fig. 4, where the upper P-Rx is composed of a multi-segment device including one segment for Dd-Rx. The lateral conduction layer of the P-Rx can then also be used for contacting the Du-Tx beneath. Many more combinations are possible.

4 CONCLUSION

Different possibilities to realize purely optical power and bidirectional data transmission have been presented and discussed. It was shown that a diversity of alternative solution exists to combine the desired functionalities into a multi-purpose integrated transceiver device.

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