Extended Abstracts of the 1993 International Conference on Solid State Devices and Materials, Makuhari, 1993, pp. 1053-1055 D-7-5

Heterostructures of Crystalline Organic and Inorganic Semiconductors for Applications in OEICs

Wolfgang Kowalsky, Christoph Rompf, and Bernd Hilmer

Department of Optoelectronics, University of Ulm,
D-89069 Ulm, Federal Republic of Germany
Phone: ++ 49-731-502-6052, Fax: ++ 49-731-502-6049

Heterostructures of crystalline organic and inorganic semiconductors for applications in waveguides, photodetectors, and integrated structures for OEICs are investigated. Layers of the aromatic compound PTCDA (3,4,9,10-perylenetetracarboxylic dianhydride, $C_{24}O_6H_8$) are deposited on different materials at substrate temperatures from T= 77 K to T = 350 K. Due to the low process temperatures optoelectronic devices can be prepared on already processed III-V and silicon wafers.

1. Introduction

Crystalline organic semiconductors offer a number of advantages in optical and electrical properties for applications in optoelectronic devices and OEICs. Waveguides, couplers, polarization splitters, and photodetectors are prepared from UHV deposited organic crystalline layers. Although III-V optoelectronic devices and silicon based electronic circuits are extremely successful as individual structures, the preparation of OEICs has not yet achieved adequate results. UHV deposition and processing of organic layers are not only compatible with the technology of inorganic semiconductors, but also offer major advantages: since no lattice matching is required, various substrate materials can be used and substrate temperatures during growth are as low as T=77K to T=350K. The integration of organic and inorganic semiconductors allows the preparation of complex waveguide structures and photodetectors on top of processed III-V devices and silicon electronic circuits.

In this paper, we present planar waveguides, photodetectors, and a first step to integrated structures based on the aromatic compound PTCDA (3,4,9,10-perylenetetracarboxylic dianhydride, $C_{24}O_6H_8$) deposited on III-V or silicon substrates.

2. PTCDA Deposition and Layer Characterization:

In contrast to spin on or dipping techniques for deposition of polymer films the crystalline organic compounds can be UHV sublimed. This vacuum deposition of films at low growth rates of about 0.1 nm/s is well reproducible and allows the growth down to monolayer structures. The molecules of organic crystals are only bonded by weak van der Waals forces. This advantage facilitates the multilayer deposition of organic solids of different crystal structures and lattice constances on complex heterostructures and the use of different substrates. Fig. 1. shows the schematic drawing of the three chamber organic molecular beam deposition (OMBD) system which essentially corresponds to the MBE (molecular beam epitaxy) of inorganic III-V semiconductors. In contrast to the MBE-process, the substrate is kept at room temperature or even cooled during growth. In case of growth on already processed inorganic devices thermal degradation is avoided.

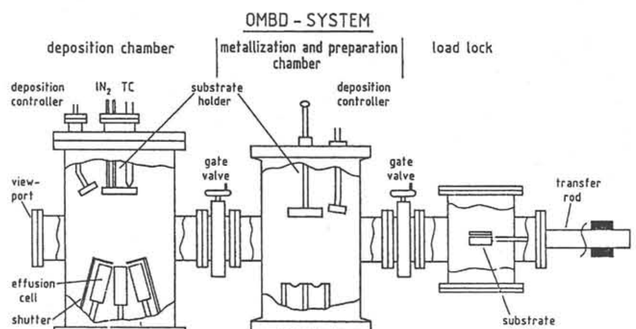

Fig. 1: Organic molecular beam deposition system.

Fig. 2 shows the transmission spectrum of a PTCDA layer. The energy of the absorption edge of PTCDA is 2.2 eV corresponding to a wavelength of 560 nm. PTCDA is transparent in the wavelength range used in optical communication systems.

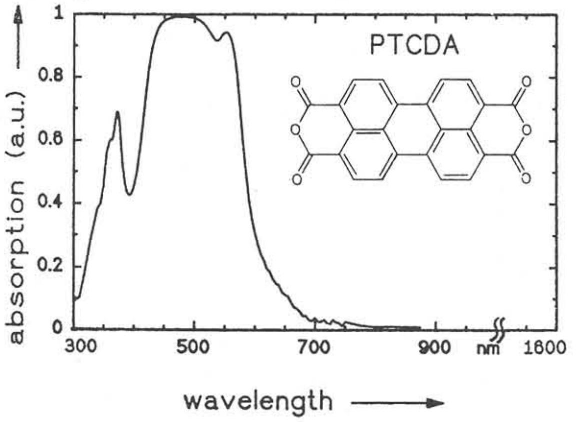

Fig. 2: Transmission spectrum of a PTCDA layer grown on a quartz substrate.

The crystal structure of PTCDA is monoclinic with two molecules per unit cell. In a planar molecular layer the molecules are oriented nearly perpendicular. From this planar net the crystal is obtained by molecular stacking. Due to this crystal geometry electrical and optical properties show distinct anisotropies. The conductivity normal to the surface is several orders of magnitude higher than the conductivity in the molecular plane. Experimentally we observed $\sigma_{\perp} / \sigma_{\parallel} = 10^2$ to 10^3 [1]. Without additional insulation or lateral structuring spreading of an injected current from a top electrode is efficiently suppressed. The PTCDA layers also show an extremely strong anisotropy of the refractive index which is $n_{par}=2.017$ in plane and $n_{perp}=1.36$ perpendicular to it [2]. This strong anisotropy of $\Delta n=0.66$ is promising for polarization sensitive devices like TE/TM filters and polarization splitters.

The molecular order of the PTCDA-layers is derived from measurements of their birefingence. Between two orthogonally oriented polarizers a PTCDA-layer is fixed normal to the optical axis and rotated. Fig. 3 is the plot of the transmitted light intensity as a function of the angle of rotation of a PTCDA-film of 500 nm thickness deposited on a quartz substrate. A Xenon-lamp and a subsequent monochromator provide the testbeam at 760 nm wavelength. The optical axis of a PTCDA crystal is tilted 11° off the substrate normal [3], which is the tilt angel of the PTCDA molecular stacks as derived from X-ray diffraction [4]. The transmitted light intensity maxima are separated by $\Delta\vartheta = 90°$. The angular orientation of these maxima does not vary across a sample diameter of 1.5 cm. This indicates the uniformity of spatial ordering of the molecular stacks.

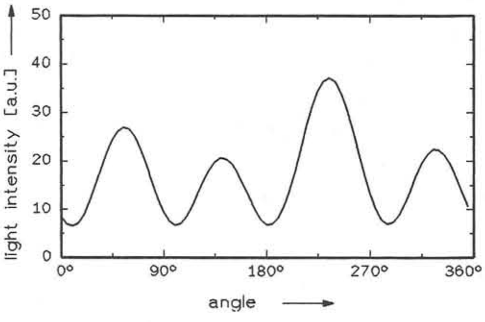

Fig. 3: Birefringence of a PTCDA-film of 500 nm thickness on quartz substrate at 760 nm wavelength.

3. WAVEGUIDES

PTCDA is well suited for waveguide applications because of low losses due to absorption and scattering in the long wavelength region (Fig.2). So far losses of PTCDA-waveguides less than 2.5 dB/cm have been published [5].

Basic waveguide structures and the photographs of the end facets of lateral single and multi mode waveguides are shown in Fig. 4.

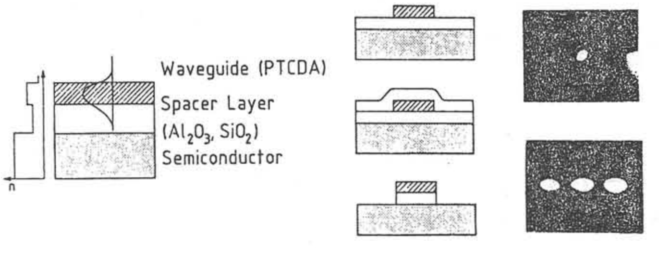

Fig. 4: Structures of PTCDA waveguides and photographs of the end facets of single and multi TE-mode waveguides.

To separate the PTCDA waveguide layer from the highly refractive III-V or silicon substrate, a dielectric spacer layer is required. Due to the strong anisotropy of the refractive index, PTCDA waveguides prepared on SiO_2 (n=1.44), SiO (n=1.87), Al_2O_3 (n=1.63) or photoresist (n=1.6) spacer layers guide only the TE mode. This strong anisotropy of the refractive index is promising for TE/TM filters and polarization splitters.

Fig. 5 shows the intensity of the transmitted light of a PTCDA/Al_2O_3 film waveguide on a GaAs substrate as a function of the angle of the incident light. To obtain guiding of TE and TM modes, the refractive index of the spacer layer has to be reduced below n=1.36 (eg CaF_2 (n=1.25)).

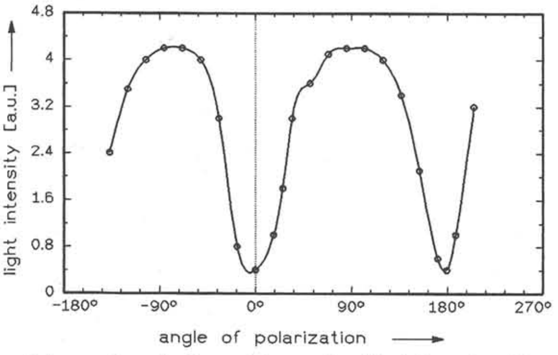

Fig. 5: Intensity of light at the end facet of a PTCDA/Al_2O_3/GaAs film waveguide as a function of the angle of polarization.

4. PHOTODETECTORS

Heterojunctions of PTCDA and inorganic semiconductors show distinct rectifying characteristics with high break through voltages of 40 V and 60 V for PTCDA/GaAs and PTCDA/InP, respectively [1]. The dark current density at V=-10 V is less than 10^{-5} A/cm^2. These results are comparable to high quality Schottky electrodes and are promising for low noise devices.

As a first example a PTCDA/GaAs-photodetector is fabricated using the conventional contact configuration of a MSM detector. Light incidence is normal to the surface. The results of the photocurrent-voltage characteristics are depicted in Fig. 6.

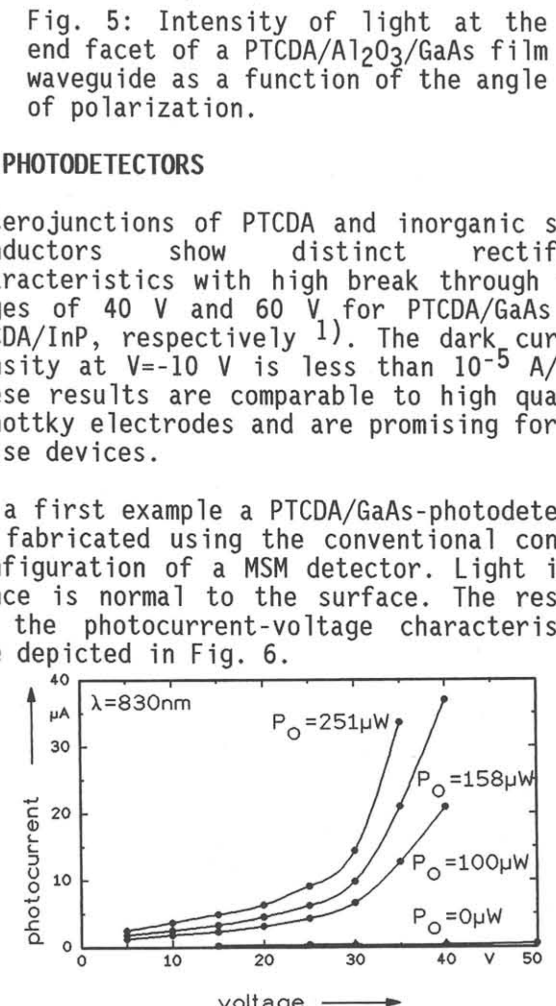

Fig. 6: Photocurrent-voltage characteristics of a planar PTCDA/GaAs photodetector.

Due to the transparency of the PTCDA electrodes reflection losses at metal electrodes are avoided and furthermore the GaAs surface is anti reflection coated by the PTCDA-layer. Limited by the experimental setup the frequency characteristics is only determined up to 4 GHz. In this frequency range no decrease of the sensitivity is observed. These results show that the PTCDA layer can be used as a transparent medium for waveguiding and as a rectifying contact for photodetection. Fig. 7 shows a step to the integration of these two devices. Whereas in the waveguide region the PTCDA layer is separated from the III-V semiconductor by a dielectric spacer, it is led down to the III-V semiconductor. In this region, the PTCDA-layer is used as the rectifying contact of the photodetector and the incident optical power from the waveguide is absorbed in the inorganic semiconductor.

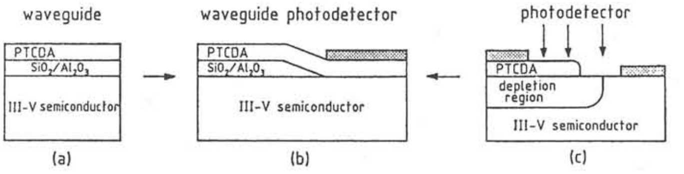

Fig. 7: PTCDA waveguide (a) and PTCDA/III-V heterostructure photodetector (c). Integration is indicated in (b).

5. Summary:

In this paper, we reported on optoelectronic devices based on organic-on-inorganic heterostructures. PTCDA layers for waveguides and photodetectors can be deposited on top of already processed III-V and silicon wafers. Process compatibility with conventional semiconductor technology, substrate temperatures below room temperature, and growth without need for lattice matching are important features with regard to applications in OEICs. The strong optical anisotropy of PTCDA is used for polarization sensitive waveguides. The organic-inorganic heterostructure provides a rectifying current-voltage characteristics which is used for photodetection.

The authors gratefully acknowledge the generous financal support by the Volkswagen-Stiftung.

References

1) W. Kowalsky and C. Rompf, in: W. Ehrfeld, G. Wegner, W. Karthe, H.-D. Bauer, and H.O. Moser: "Integrated optics and micro-optics with polymers", Teubner Texte zur Physik, in press.
2) D.Y. Zang, F.F. So, S.R. Forrest, Appl.Phys.Lett. **59** (1991), pp. 823-825.
3) F.F. So, S.R. Forrest, Y.Q. Shi, W.H. Steier, Mat.Res.Soc.Symp.Proc. **198** (1990), pp 71-77
4) S. R. Forrest, M. L. Kaplan, and P. H. Schmidt, J.Appl.Phys. **55** (1984), pp. 1492-1507.
5) D.Y. Zang, Y. Q. Shi, F.F. So, S.R. Forrest, and W.H. Steier, Appl. Phys. Lett. **58** (1991), pp. 562-564.