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Photonic Devices Based on Crystalline Organic Semiconductors for Optoelectronic Integrated Circuits

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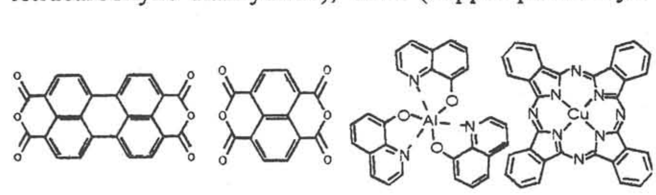
Due to room temperature deposition under ultra high vacuum conditions with no need for lattice matching crystalline organic thin film structures can be prepared both on dielectric substrates and on top of completely processed III-V or Si wafers. In this contribution we discuss the growth and performance of organic semiconductor electroluminescent devices, waveguides, and photodetectors and present a concept for optoelectronic integrated circuits based on this new class of materials.

1. Introduction

Conventional integration of electronic circuits mainly prepared on Si substrates and photonic devices composed of inorganic semiconductors on a single chip requires lattice mismatched heteroepitaxy of III-V semiconductor compounds on Si wafers and high temperature growth conditions. Thermal damage to already processed Si circuits and the optical quality of the epitaxial layers severely restrict the performance of inorganic optoelectronic integrated circuits (OEICs) compared to the characteristics of the individual structures. From the wide spectrum of organic compounds polymeric and crystalline organic semiconductors show remarkable electrical and optical properties and offer a promising chance to overcome these limitations. Organic and organic-on-inorganic heterostructures for electroluminescent devices, waveguides, couplers, diodes, and photodetectors have been successfully fabricated[1,2]. In contrast to the spin-on deposition technique often used for polymers crystalline organic semiconductor thin films are grown under ultra high vacuum conditions at substrate temperatures from 77 K to 300 K. Both monolayers for quantum well structures and several microns thick multilayer structures are obtained without breaking the vacuum and with no lattice matched growth required due to the weak van der Waals bonding forces between the molecules. These inherent advantages of organic semiconductors allow for the fabrication of organic-on-inorganic OEICs, intrachip optical interconnects on top of already processed Si wafers, independent components for chip-to-chip communication and displays on separate dielectric substrates.

2. Organic semiconductor materials and molecular beam deposition technique

The molecular structures of the organic semiconductor materials used for devices described in this paper are shown in Fig. 1. PTCDA (3,4,9,10-perylenetetracarboxylic dianhydride), NTCDA (1,4,5,8-naphthalinetetracarboxylic dianhydride), CuPc (copper phthalocyanine), and Alq (8-hydroxyquinoline aluminum) are sublimed under high vacuum conditions at a base pressure of less than 10^{-8} mbar. The substrate is kept at room temperatures or even cooled with liquid nitrogen. The growth rate is measured by a quartz oscillator thickness controller. For molecular monolayer deposition growth rates as low as 0.1 nm/s can be achieved. In contrast to the spin-on technique for polymeric films this deposition methode yields a high reproducibility. Fig. 2 shows the four chamber UHV Organic Molecular Deposition System (OMBD). Its arrangement follows the concept of conventional III-V semiconductor MBE systems and consists of a load lock chamber with magnetically coupled transfer rod, a preparation and metallization chamber, a growth chamber for the organic materials,



PTCDA NTCDA Alq CuPc

Fig. 1: Molecular structures of PTCDA, NTCDA, Alq, and CuPc.

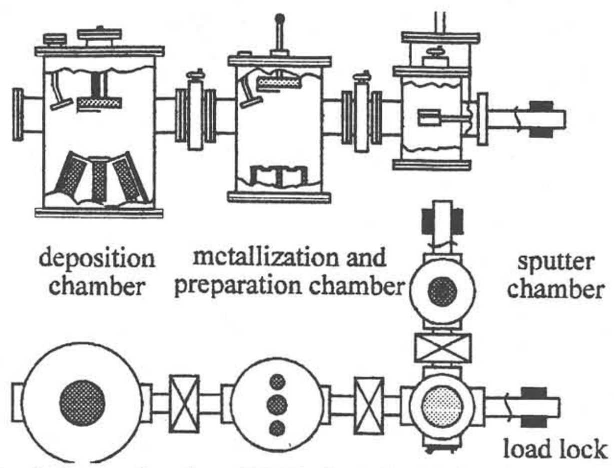


Fig. 2: Four chamber UHV Organic Molecular Beam Deposition System (OMBD).

and a sputter chamber. This setup allows to grow subsequent layers of various organic semiconductors, metallic contacts, ITO (indium-tin-oxide) transparent contacts, and dielectric films under permanent high vacuum conditions.

3. Organic electroluminescent devices

The structure of a two-layer organic electroluminescent cell[3,4] is depicted in Fig. 3. On top of an ITO coated glass substrate a 100 nm thick CuPc hole transport layer, an Alq emitter and electron transport layer, and a Mg/In top contact are deposited. Bright green cw emission through the glass substrate is observed at room

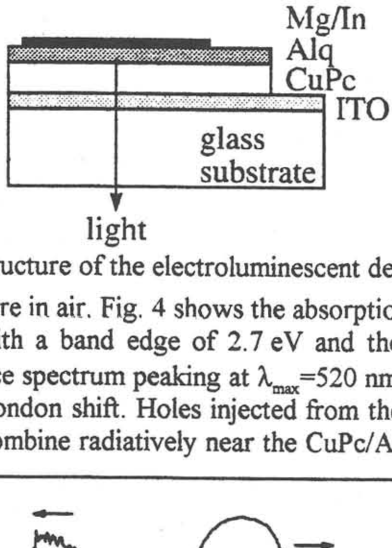


Fig. 3: Structure of the electroluminescent device.

temperature in air. Fig. 4 shows the absorption spectrum of Alq with a band edge of 2.7 eV and the electroluminescence spectrum peaking at λ_{max}=520 nm due to the Franck-Condon shift. Holes injected from the ITO electrode recombine radiatively near the CuPc/Alq interface

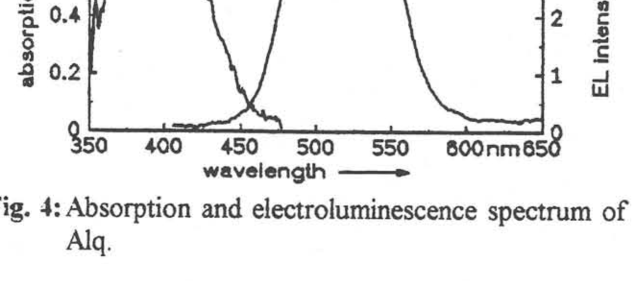


Fig. 4: Absorption and electroluminescence spectrum of Alq.

with electrons injected from the Mg electrode. The hole transport layer effectively prohibits any significant transport of electrons and therefore confines the electron-hole recombination within the Alq layer. The thickness of the emitter layer is extremely critical to the external quantum efficiency and to the current-voltage characteristics of the device. Fig. 5 shows the V-I characteristics for structures with an Alq layer thickness of 45 nm, 60 nm, and 90 nm. The highest quantum efficiency is obtained for a 45 nm thick Alq layer (Fig. 6). Below this

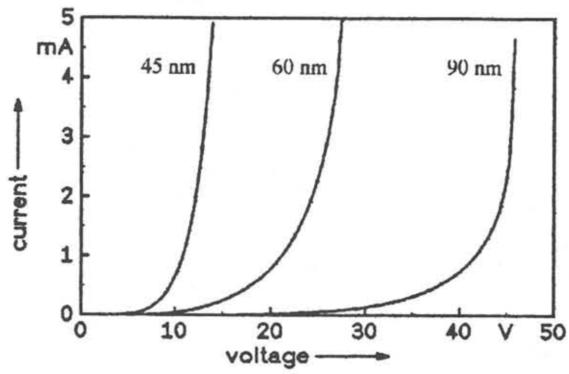


Fig. 5: Alq layer thickness dependent V-I characteristics of the electroluminescent devices.

optimum thickness a significant number of holes injected from the CuPc layer reaches the negative electrode without radiatively recombining with electrons. A thicker layer results in holes trapped in the Alq layer followed by non-radiative recombination.

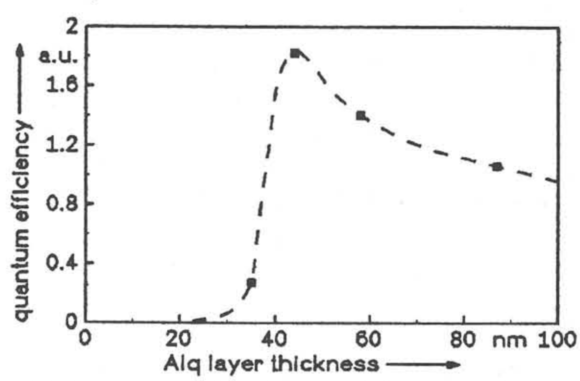


Fig. 6: Influence of Alq layer thickness on quantum efficiency.

4. Waveguides

PTCDA, NTCDA, and CuPc are well suited for waveguide applications due to their high transparency in the appropriate wavelength regions. The low refractive organic waveguide is separated from the high refractive inorganic semiconductor substrate by a dielectric spacer layer, e. g. SiO_2 (n=1.44), SiO (n=1.87), or Al_2O_3 (n=1.63). The lateral confinement of the light is achieved in a stripe geometry defined by conventional lift-off technique. A 3-dimensional plot of the light intensity at the end facet of the waveguide is shown in Fig. 7.

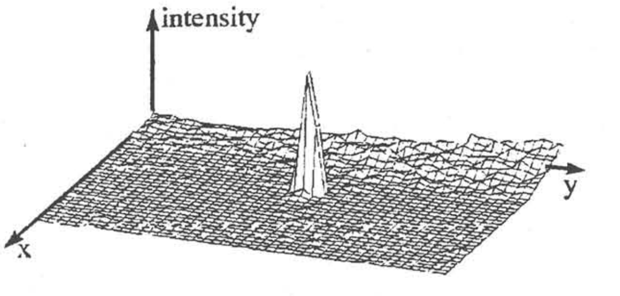


Fig. 7: 3-dimensional plot of the light intensity at the end facet of the waveguide.

5. Photodetectors

Organic-on-inorganic heterostructure form rectifying quasi-Schottky contacts with high reverse breakdown voltages and low dark currents well suited for photodetector applications. As an example Fig. 8a shows the structure and the current-voltage characteristics of a PTCDA-on-Si heterostructure. The dark current is as low as 10^{-5} A/cm^2 at V_R=10 V, and the breakdown voltage of 90 V is limited by carrier multiplication in the inorganic material. In contrast to metal electrodes the PTCDA and ITO layers are transparent in the infrared spectral region and avoid shadowing effects, layers designed for a thickness of $\lambda/4$ serve as anti-reflection coatings. A photodetector with a metal-(organic semiconductor)-metal structure deposited on a dielectric substrate is depicted in Fig. 8b. Light is absorbed in the CuPc layer and generates excitons that dissociate into free electrons and holes and contribute to the photocurrent.

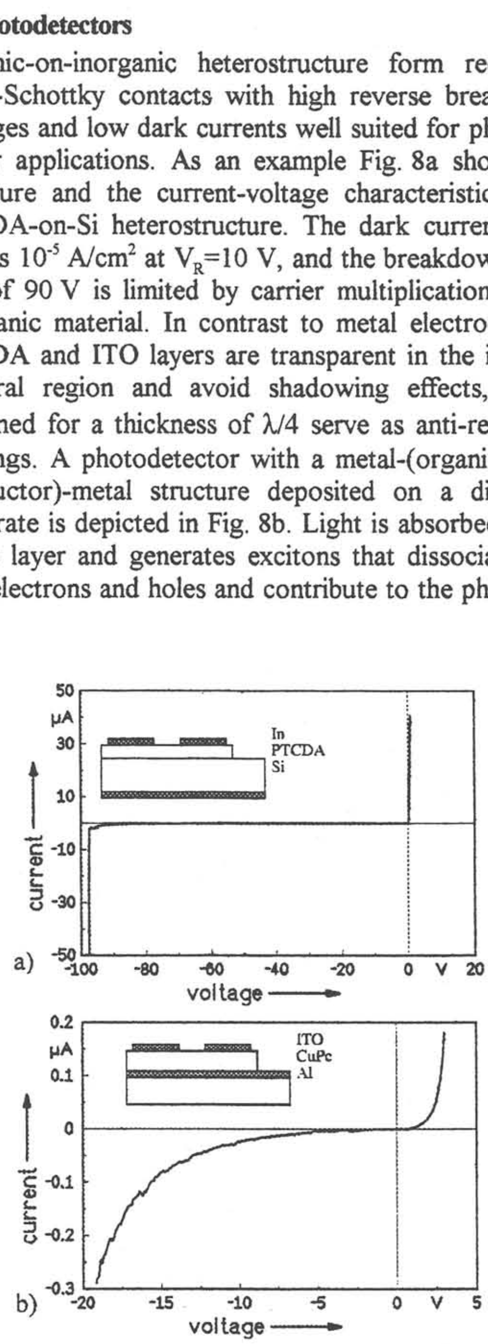


Fig. 8: Structure and V-I characteristics of a) a PTCDA-on-Si and b) an Al-CuPc-In photodector.

6. Optoelectronic integrated circuits and optical interconnects

Organic semiconductor electroluminescent devices, waveguides, and photodetectors are well suited for OEICs and optical interconnects on top of processed Si wafers and on dielectric substrates. Fig. 9 shows a novel concept for intrachip and chip-to-chip optical interconnects based on this new class of materials. Thin films for intrachip optical interconnection devices are deposited on top of processed Si chips. Independent active optical interconnects for chip-to-chip communication are grown on separate dielectric substrates. The electroluminescent device and the photodetector are integrated with a waveguide and wire-bonded to the Si circuits. Critical and expensive laser-to-fiber and detector-to-fiber couplings are not necessary.

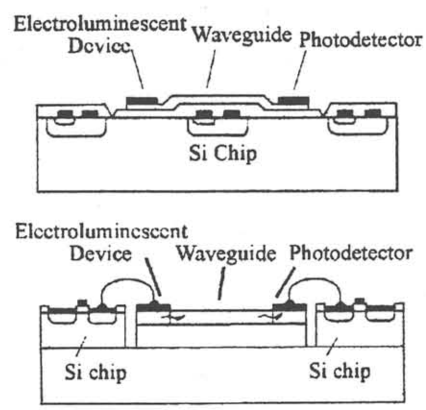


Fig. 9: Intrachip and chip-to-chip optical interconnects.

7. Summary

In conclusion, the room temperature growth of the organic compounds PTCDA, NTCDA, Alq , and CuPc by organic molecular beam deposition (OMBD) allows to prepare photonic devies on dielectric substrates and on processed Si wafers. Integrating the individual organic components electroluminescent device, waveguide, and photodetector and the Si circuits is a promising approach towards the realization of OEICs and optical interconnects.

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