プログラム名：量子人工脳を量子ネットワークでつなぐ高度知識社会基盤の実現
PM 名：山本 喜久
プロジェクト名：量子シミュレーション

委 託 研 究 開 発

実 施 状 況 報 告 書（成果）

平成 29 年度

研究開発課題名：

Development of semiconductor-based quantum simulators

研究開発機関名：

ウルツブルグ大学

研究開発責任者

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1. Activities, Accomplishment and Findings

In the fiscal year 2018 the Würzburg group has continuously worked on the fabrication of ultra-high quality, low disorder microcavities for the use in ion implantation experiments. These cavities allow for the condensation of polaritons with a large excitonic fraction, which is a crucial prerequisite for the realization of trapped heavy polaritons, using ion implantation. In close collaboration with Dr. Mike Fraser and the group of Prof. Tarucha, a first set of Honeycomb-, Kagome-, and Square-Lattices as well as single traps for calibration purposes have been realized.

Some preliminary results have already been published in C. Schneider et al., Reports on Progress in Physics 80, 1 (2016) [see also fig. 1]. A thorough publication on the ion implantation process into planar GaAs- based microcavities in order to tune the excitonic transition (or the photonic mode) is still in preparation.

In previous experiments the planar cavity has been pattered with a SiO_2 mask of the chosen geometry in order to block ion implantation at this points. After successful ion implantation the SiO_2 mask is removed and the sample can be characterized by photoluminescence measurements.

A first real-space measurement of an ion implanted polaritonic lattice is presented in Fig. 1 c. It is clearly visible that the polaritons are precisely confined in local traps of identical potential depth in addition, polariton condensation could be demonstrated on microcavities after the area of investigation has been treated with ion implantation, showing that the structural quality of the crystalline material remains intact. After a first characterization with the focus on the implantation proccess the lattices are going to be transferred to Technische Physik at the Würzburg University for a detailed investigation on the band-structure formation and dispersion measurements.

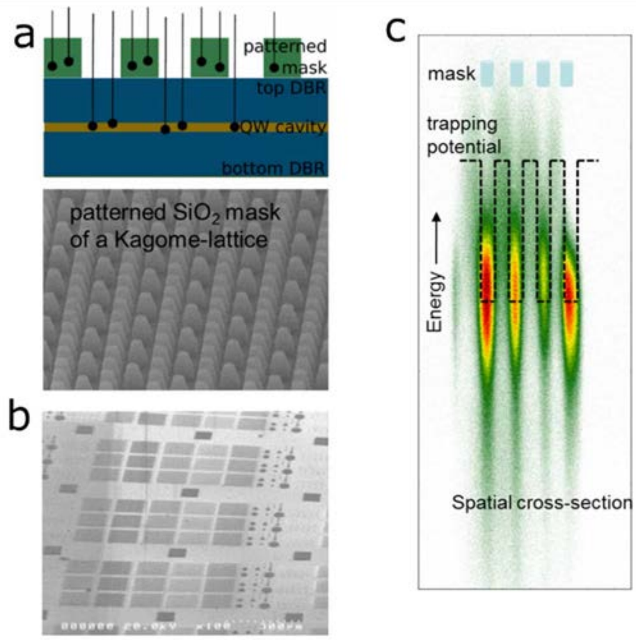

Figure 1 | Ion implantation technique for the creation of heavy polariton lattices. (a) Schematic and scanning electron microscope image of the processed GaAs-based, high-Q micricavity from Würzburg. The conical structures in the image are the SiO2 mask, here in a Kagome geometry. (b) Overview scanning electron microscope image of the sample featuring Honeycomb-, Kagome-, and Square-Lattices as well as single traps for calibration purposes. (c) Real-space photoluminescence measurement of polartons in a potential landscape, created by ion implantation.

Following this efforts the Würzburg group has specifically provided an ultra-high quality microcavity following the exact specifications of Dr. Mike Fraser and has provided multiple sample pieces for extended ion implantation tests and experiments (please see Fig. 2 for an example). Goal is the deterministic creation of topologically non-trivial complex potential using ion implantation patterns in e.g. a Kagome lattice.

```
set(Al20GaAs, 58.2nm)
set(AlAs, 67.2nm)

/* Buffer
layer(GaAs, 400nm, Buffer)

/* Bottom DBR
for(x,35,1)
layer(Al20GaAs, $Al20GaAs, DBR)
layer(Al2As, $AlAs, DBR)
next(x)

/* Bottom DBR-Matching Layers
layer(Al20GaAs, $Al20GaAs,DBR)
layer(AlAs, 67.2nm,DBR)

/* Cavity
layer(Al40GaAs, 97.5nm, Al40GaAs)
for(x, 3, 1)
layer(GaAs, 7nm, GaAs)
layer(Al40GaAs, 4nm, Al1As)
next(x)
layer(GaAs, 7nm, GaAs)
layer(Al40GaAs, 4nm, Al40GaAs)

/* Top DBR-Matching Layers
layer(AlAs, 41.2nm, DBR)
layer(Al20GaAs, 58.2nm,DBR)

/* Top DBR
for(x,29,1)
layer(AlAs, $AlAs, DBR)
layer(Al20GaAs, $Al20GaAs, DBR)
next(x)

/* Matching Layer & Cap
layer(AlAs, 54.9nm, DBR-Matching Layer)
layer(GaAs, 10nm, Cap)
```

Figure 2 | Provided ultra-high quality microcavity sample. (left) Image of a quarter waver microcavity. (right) Exact sample specification need for ion implantation experiments.

In addition to the employment of excitonic confinement using ion implantation, the group at Technische Physik has continued their work on photonic confinement, using classical etching techniques. Specifically the use of half-etching has the distinct advantage, that a strong photonic confinement can be created without etching through the GaAs quantum well, avoiding a defect exciton band.

Using this technique for the pursuit of topologically non-trivial effects in a hybrid photonic structure the Würzburg group at Technische Physik was able to demonstrate the very first demonstration of an exciton-polariton topological insulator. The group used a Honeycomb geometry, half-etched into a GaAs-based microcavity. By using a combination of TE-TM splitting, acting as effective spin-orbit interaction and Zeeman splitting, breaking the symmetry under magnetic field the group was able to demonstrate robust, chiral and unidirectional edge transport, topologically protected from scattering from defects, corners or the bulk material. The work has been pre-published on arXiv: S. Klembt et al., Exciton-polariton topological insulator arXiv:1808.03179 (2018) and the revised version has been accepted for publication and is soon to appear in Nature. A short visual overview is provided in Fig. 3.

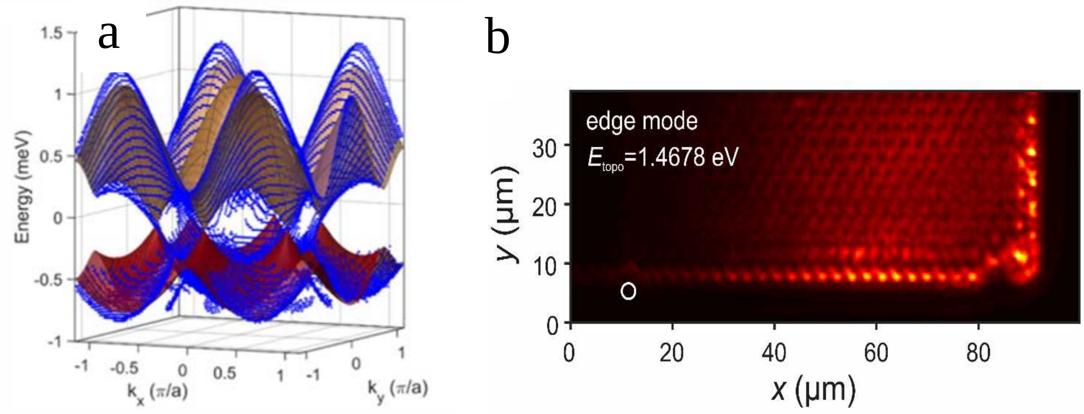

Figure 3 | Polaritonic honeycomb lattices for topologically nontrivial effects. (a) Experimental photoluminescence scan (blue) and tight-binding model of the typical graphene dispesion. The data agrees very well with the model, clearly showing the six Dirac cones at the K and K' points. (b) Real space photoluminescence tomography of the polariton topological insulator showing the topological edge mode going around the corner from the zigzag to the armchair termination.

Furthermore, the Würzburg group has intensified their efforts towards realizing electrical operation of such polariton lattices. By optimizing a sophisticated doping and contacting scheme, the Würzburg group has been able to demonstrate electrical pumping of such a lattice for the first time. For a detailed description of this work please refer to: H. Suchomel et al., A plug and play platform for electrically pumped polariton simulators and topological lasers arXiv:1803.08306 (2018).

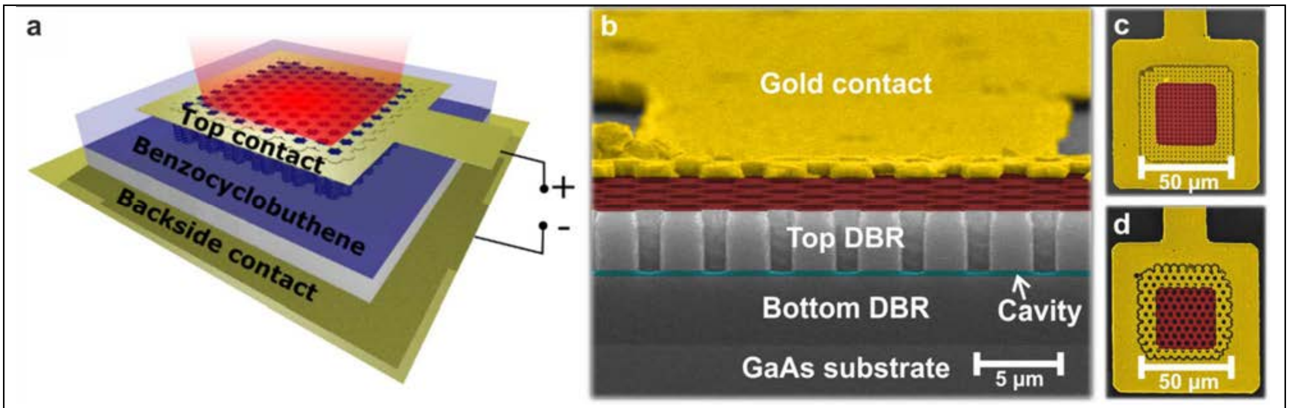

Figure 4 | (a) Schematic of the investigated device showing the half-etched polariton lattice, planarized with benzocyclobutene with top and bottom electrical contacts. (b) SEM image of the processed device with a view tilted above the cleaved edge, cutting the device in half. A 200 nm thin gold contact (yellow) has been deposited on an etched two-dimensional lattice (red) in order to inject a current into the microcavity structure. The quantum wells (QWs) have been placed in the field maximum inside a cavity (cyan). The n-contact is deposited on the plane backside of the GaAs substrate. To avoid etching damage to the QWs, the etching depth has been adjusted in order to stop close above the cavity region. (c-d) SEM images of the investigated lattice devices in top view configuration. The deposited gold contact (yellow) surrounds the etched lattices (red) with an overlap of one to two lattice constants. The whole lattice field has an edge length of ~ 50 µm with (c) depicting the investigated square lattice and (d) the honeycomb lattice.

2. Outreach, Events and Other Activities

None