The Vision

neutral-atom manipulation using integrated micro-devices

combining the best of two worlds:
• cold neutral atoms - a well controllable quantum system
• technologies of nano-fabrication, micro-electronics, micro-optics

Take the tools of quantum optics and atomic physics and make them robust and applicable by miniaturizing and integrating them using the techniques of nano-fabrication, micro-electronics and micro-optics.
• create a tool box for building quantum devices
MINIATURIZATION and INTEGRATION

Electronics

Optics

Matter waves

mesoscopic matter wave optics similar to quantum electronics

• Microscopic potentials

• Atom Chip: integrated mesoscopic matter wave devices

• Atoms close to warm surfaces

• Atom Optics on Atom Chip

• Atom detectors

Review:
www.AtomChip.org
Microscopic Potentials for Neutral Atoms

Interactions for micro traps

Magnetic Potentials
Magnetic moment of the atom interacting with the magnetic field

\[ U_{\text{mag}} = -\vec{\mu} \cdot \vec{B} \]

\[ U_B[\mu\text{K}] \propto 67 \times B \ [\text{G}] \]

strong field seeker: \( U_{\text{mag}} < 0 \)

weak field seeker: \( U_{\text{mag}} > 0 \)

Electric Potentials
Electric polarizability interacting with an electric field

\[ U_{\text{el}} = -\frac{1}{2} aE^2 \]

Li-Atom: \( \alpha = 24 \text{A}^3 \)

\[ U_E[\mu\text{K}] \propto 98 E^2 [\text{V/\mu m}] \]

Optical Dipole Potentials
Dipole potential:

\[ U_{\text{dip}} \propto -\alpha(\omega) I(\vec{r}) \]

Blue detuning:
Atoms trapped from intensity maxima

Red detuning:
Atoms repelled from intensity maxima

Use reflective properties of Atom Chip for 1D, 2D and 3D standing-wave potentials

\[ U(x) = \frac{\hbar \Omega_0}{4\Delta} \left( 1 + \cos \frac{2\pi x}{\lambda} \right) \]

Modulate magnetic traps using optical potentials (Optical lattice QIP on chip)

Modify optical traps with magnetic (electric) potentials

Structure the dipole traps by holographic means (spatial light modulators)

For a review see R. Grimm et al.
Magnetic Interaction
Atom and a Current

Quantum wire:
current carrying wire
\[ \vec{B}(\rho) \propto I \frac{1}{\rho} \frac{\partial \phi}{\partial \rho} \]

Vector Coulomb Problem

adding a bias field creates a potential minimum on side of wire (Frisch, Segre 1932)

potential depth: bias field
potential gradient: \(1/I\)

Mount wire on a surface:
Use nanofabrication to build mesoscopic structures.

Achievable: level spacing of >1 MHz
DESIGNS
Surface Mounted Atom Optics

Guides
with external bias field

1-wire

2-wire

3-wire

4-wire

with on chip bias field

See also: J.H. Thywissen et al., EPJ D 7, 361 (1999)

How to build a trap
minimum of the potential is given by the angle between the wire and the bias field

Single wire: Side guide

U-current: 3D Quadrupole

Z-current: Ioffe-Pritchard trap


ATOMS and WIRES
microscopic guides and traps


1995-99 Innsbruck (cold atoms)

Kepler Guide

I = 1 A

0 ms

5 ms

9 ms

10 ms

15 ms

20 ms

Schmiedmayer IQEC 92; PRA 52, R13 (1995)
Denschlag et al. PRL 82, 2014 (1999)
A. Haase Diplomarbeit (2000)
Electric Interaction
Atom and Charged Wire

Review:

Neutral Atom and Charged Wire
1/r^2 Potential

Classical Trajectories
No stable orbits!

Interaction Potential
\[ U_{INT} = \frac{1}{2} \alpha E^2 = -\frac{2aq^2}{r^2} \]

Angular momentum
\[ U_{Lz} = \frac{L_z^2}{2Mr^2} \]

Total potential
\[ U_{Eff} = U_{Lz} + U_{INT} = \frac{1}{2Mr^2} \left[ L_z^2 - L_{crit}(q) \right] \]

Critical angular momentum:
\[ L_{crit} = 2\sqrt{\alpha Mq} \]
$1/r^2$ potential
quantum fall towards the center

Quantized of Absorption Cross Section for $R_{wire} \rightarrow 0$
quantum limit for $R_{wire} \ll \lambda dB$

Linecharge:
$U_{Eff} = \frac{L_z^2 - L_{crit}^2(q)}{2\sqrt{\alpha M} q}$
$L_{crit} = 2\sqrt{\alpha M} q$

One partial wave after the other
($h\ell < L_{crit}$) is absorbed
$\rightarrow$ quantum steps in absorption cross section
$q_{\Delta \ell = 1} = \frac{\hbar}{2\sqrt{\alpha M}}$
$\Delta q_{\Delta \ell = 1} \approx 1pC$
$\Delta U_{\Delta \ell = 1} \approx 0.2V$

For $kR_{wire} > 1$ the steps wash out
but reappear for high $\ell$


Decay experiments
3 different wire diameters

Measuring the fall onto the wire by trap decay

Denschlag et al. PRL 81, 737 (1998)
Van der Waals Potential will make wire radius appear thicker.

Simple model:
Integrating the contribution over the finite size of the wire

Preliminary data ($v=50$ cm/s): 
- $r_w = 0.5 \mu m \quad r_{eff} \sim 0.8 \mu m$
- $r_w = 1.8 \mu m \quad r_{eff} \sim 2.3 \mu m$

large effect for thin wires
**ATOM CHIP**

fabrication of microscopic atom traps

Adapted nanofabrication technique to needs of Atom Chip (Weizman, Innsbruck/Heidelberg, TU-Vienna)

**Features:**
- Chip = mirror → wires are defined by etchings
- structures down to 1 µm
- current densities > 3 \(10^7\) A/cm\(^2\)
- high voltages > 500V
- trap frequencies > 1MHz
- ground state size ~10 nm
- multi layer possible

**Other techniques** (MPQ, Orsay, Tübingen …):
Thin film hybrid technology

- Larger structures
- Large cross section
- High currents

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**Atom Chip Fabrication**


Adapted from standard semiconductor nanofab.
Innsbruck, Heidelberg, Weizmann, TU-Wien
Heating of the Wire

Model the heat transfer to the substrate:
- Contact resistance (fast time scale)
- Heat conductivity into the sample (slow time scale)
- Finite thickness of sample

Important:
- Heat capacity
- Heat conductivity

For us the choice:
- Si
- GaAs

Thin wires are limited by fast heating: \( j_{\text{max}} \geq 10^8 \) is possible


ATOM CHIP implementation

Chip with integrated lens

Support structure underneath the chip

Heidelberg

Orsay

Hannover

nano fabricated chip compatible with \( p \leq 10^{-11} \) torr

thin film hybrid technology

ACQUIRE, ACQP
Atom Chip
how to cool, load and play with ultra cold atoms

EXPERIMENTAL SETUP
cooling close to surface

quadrupole

camera 1

camera 3

ibk - hd

oven

laser beams

camera 2

picture of mirror MOT
**ATOM CHIP STATUS**

experiments with thermal atoms

- Innsbruck
- Heidelberg

Loading mesoscopic traps

Dynamic Beam Splitter

Beam Splitter

Electric traps

1 μm structures

Top view front view

Continuous Loading

Vertical traps guiding in arbitrary direction

- trap frequencies > 1 MHz
- trap ground state < 30 nm
- trapping with on-board bias field
- structures down to 1 μm
- moving, splitting etc …

www.AtomChip.org

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**INTERFEROMETER**

on the Atom Chip

Experiment with thermal atoms

Top view

-15 ms

-5 ms

5 ms

15 ms

25 ms

1 mm

side view

Problem: minimum of the potential changes during the splitting.
Manipulation with Electric Fields

**Dynamics**
- Electric fields can be varied
- Linearly summed
- Atomic transport "motors"
- Splitting and recombining

**Electric Motor**

[Electric Motor diagram]


BEC in MICRO TRAP

**Heidelberg**

Many groups:
- Tübingen, MPQ, ORSAY, IC, MIT, JILA, Brisbane...

With a BEC we have a reservoir of motional ground state atoms as a source for the experiments

**High atom density**
- The matter wave optics will be non-linear
- If interactions dominate: strongly correlated systems

**MOT > 3 10^8 atoms @ 70 μK**
**Magn. Z trap > 10^8 at. @ 250 μK**

**Compress**
- Trans.: ~500 Hz, ~400 G/cm
- Long.: ~50 Hz

**RF-Evaporation**
- ~10 sec

**BEC**
- 3 10^5 atoms @ T_c ~ 500 nK
- Independent of chip structure
Atoms close to surfaces

**Why go close to surface**

- **Tight confinement (transversal)**
  - 1d-physics, QuInfo
  - Confinement proportional to current density $j$
  - $j$ depends on the removal of Ohmic heat
  - better for small wires

- **Small potentials for tunnelling coupling**
  - Minimum structure size of the potentials
  - $\sim$ distance to the surface
  - size $\sim 1\mu m$

- **Small potentials for quantum tweezer**
  - loading single atoms

- **Manipulating mesoscopic ensembles**
  - .........
Measure Distance from the Surface

Need to consider the light wave close to the surface

Small heights are extrapolated from directly measurable values (based on finite wire size)

Atoms close to surface

The bad guy: Johnson Noise

Life time of trap

Pure exponential decay of trap observed over up to >2 orders of magnitude

Qualitatively the same behaviour but quantitative differences

- Steeper dependence with height
- Shorter lifetime for smaller distances
- Long lifetime for moderate distances (1s at ~5µm)
- Differences between wires (tech. noise?)

Hight calibration still uncertain by ~ 1µm
Atoms Approaching the Surface
Roughness of the magnetic potential

Observed potential at different heights

Power spectrum of roughness in terms of potential energy
(1 µK = 15 mG)

From where do the disorder potentials come from

- Atoms are trapped in the minima of potentials created by the subtraction of two large fields.
- Minimum in that plane depends on the angle between these two fields.
- Sensitivity to changes in the current direction which are not orthogonal to the bias field.
- Sensitivity: thermal atoms: 1G ~ 67 µK BEC: chem. potential (~1-10 mG) sensitivity < 10^{-5} rad

Proposal:
- Roughness of the wire edge causes the current to deviate from a straight flow (we choose evap. gold and nanofab.) for theory see: Daw-Wie Wang et al. PRL 92, 076802 (04).
- Imperfections in the surface of substrate (we chose Si and GaAs).
- Disordered current flow due to grain size, inhomogeneities, ... in the wire.
Roughness of the magnetic potential evaporated gold Atom Chips

Heidelberg/WIS

No fragmentation for a thermal cloud even at $T \sim 500\text{nK}$

Some fragmentation for a BEC below $10\ \mu\text{m}$ from surface

Disorder potentials $\sim 100\text{nK}$ or smaller

Expanding BEC shows fingers

BEC near surfaces

BECs are a more sensitive probe $\Delta U < 10^{-13}\text{eV}$

Fragmentation becomes visible

typical scale given by chem. potential of BEC ($\sim 100\text{nK}$)

- Wire can be scanned by variation of longitudinal confinement
- Disorder potentials are stable in position and time

Heidelberg
Origin of disorder potentials

Possible sources:

- gravitation (~100nK/µm)
- electric fields
- magnetic fields (irregular currents)

Scan at equal height but varied currents
Disorder potentials normalized to $\Delta B/B$
Traces equal within $\Delta B/B \sim 3 \times 10^{-6}$
$\Delta U < 10^{-13}$ eV down to $d<5\mu m$

Chip surfaces

Lithographically patterned atom chips
Innsbruck-Heidelberg-Weizman

Electroplated chips
(Orsay) Estève et al., cond-mat 2004
What causes the disorder potentials?

How to decide?
Measure potentials on a wide wire (width >> height of atoms) will see the local properties of the current.

Mapping disorder potentials

100 µm wide wire

Strong height scaling even though the distance to wire is much smaller than the wire width?

? Can the edge of wire be the cause of the disorder potential?
**Edge or local effect?**

Scaling of disorder potentials near a broad wire (100µm)

- fragmentation increases as the surface (not edge) is approached
- pure edge effect leads to different scaling
- Simple local model gives better agreement
- k-dependence $\sim 1/k^2$

**What causes the disorder potentials?**

Important contribution from the local properties
BEC can be placed far from trapping wire but close to a different structure by rotating the bias field. Atoms held with 10µm wire above 100µm wire.

- **Magnetic disorder**
  - 100µm: 0mA
  - 40mA

- **Electric disorder**
  - 50µm: 0V
  - 50V

Atom Optics on Atom Chip

Some 1-d experiments

www.AtomChip.org
Condensing with E-field

Thermal cloud

- $N = 1.3 \times 10^5$
- $T = 1.1 \mu K$
- Height = 10 $\mu$m
- $\nu_{\text{long}} \sim 5$ Hz
- $\nu_{\text{trans}} = 17$ kHz
- TOF = 10 ms

Condensing with E-field

$U = 0$ V

$U = 3.5$ V

Heidelberg
Condensate formation in dimple trap

- thermal atoms just above $T_c$ in a 1d trap
- at 0ms electric dimple is suddenly created
- 1d BEC forms slowly
- BEC becomes larger and 3d
- equilibrium reached after ~80ms

Final cooling

825 kHz

792 kHz

760 kHz

TOF = 16ms  
Duration of sequence 60 ms
BEC propagation in 1d guide against a background

TOF = 16ms
Duration of sequence 5ms

- BEC is formed in 3d dimple
- off-center release to elongated (1d) trap by sudden (<1µs) switching off of dimple voltage
- background gas temperature \( \approx T_C \)
- movement of edge at \( \approx 5\text{cm/s} \)
- thermalization into equilibrium state (centered cloud at \( T_C \)) on slower time scale (\( \approx 100\text{ms} \))

Moving cloud in 1-d

Displace the potential longitudinally

\[ \Delta x \]

See the formation of a dense core at first 'reflection'
Appearance of regular fringes

IV 2004
TOF expansion: 1-d BEC
sharp lines in expansion after fast cooling

Parameters: fast cooling time (start of ramp to picture as short as 10ms)
sound propagation along condensate >200ms
1-d regime: $\mu \omega$
Suggestion: sharp lines are a sign of domain formation in the order parameter
during the phase transition

Integrating light on Atom Chip
Atom detection
INTEGRATION OF LIGHT ON THE ATOM CHIP

Goals: Preparation, Manipulation, Detection of atomic states on the Atom Chip

Tools: Micro optics: cavities, lenses, waveguides

Techniques of coupling to the atoms: Two mirror resonators, evanescent fields of micro spheres or micro discs, SNOM techniques, fiber cavities

Longtime goals: State selective, non-demolishing, single atom detection; Integration of all micro optical elements, including light sources, onto the Atom Chip

Detection of atomic states on the Atom Chip
Micro optics: cavities, lenses, waveguides
- Two mirror resonators
- Fiber cavities
- SNOM techniques

Setup:

Parameters:
- 5 µm core
- 5 µm gap
- Finesse 500
- >3σ detection

setup:

Parameters:
- 5 µm core
- 5 µm gap
- Finesse 500
- >3σ detection

www.AtomChip.uni-hd.de
Test Setup

To learn stabilization schemes for the cavity, preliminary experiments are performed using a standard mirror cavity and cold atoms being dropped from a 6-beam MOT above.

Cavity parameters

Chosen to be comparable with fibre setup: spherical mirrors with transmission $T=0.001$, radius of curvature $r=10$ mm at a distance of $L\approx 19.9$ mm form a waist of $w_0\approx 10 \mu$m. A Finesse of up to $F\approx 2000$ was measured.

Detecting Atoms in micro traps

First signals

Regime of bistability

Cavity with Finess $\approx 500 \ w\approx 12 \ \mu$m

A. Haase 2003
First fiber cavity test experiments

Fibre cavity of finesse 110 formed by dielectric mirrors at the outer fibre ends. A gap of 5 microns is included. The cavity length is scanned using a piezo stretcher, no alignment needed.

- $8\sigma$ detection of a single atom in 10 $\mu$s
- Finess > 1000, w ~2.5 $\mu$m with front mirrors and gap up to >50 $\mu$m

CONCLUSION

- Atom Chip fabrication including integration of light on the Atom Chip
- Load versatile atom traps
  - surpassed the required ground state sizes for QIPC
  - multiple traps, transport, qubit selective manipulation
  - BEC on Atom Chip
- Small disorder potentials -> mesoscopic exp.
  - Controllable electric and magnetic disorder
  - New tool for surface physics
- 1-d Experiments on Chip
  - 1-d thermal cloud ($T \sim \hbar \omega$)
  - 1-d BEC ($\mu \ll \hbar \omega$) up to $\gamma \sim 0.1$
  - BEC far from equilibrium, look at dynamics of phase trans.
  - BEC formation in disordered potentials
- Detector designs for $>3\sigma$ in 10 $\mu$s
  - Detection of guided atoms with a cavity

Review:
Atom Chip Future

- Bosons - Fermion and mixed systems
- Mesoscopic physics
  - Optics, interference, coherence
- Model Systems
  - Low dimensional systems (1-d, 2-d)
  - Disorder physics
  - Excitations
  - Spin systems, Spin-Charge separation
  - Superconductivity
  - ..........
- Precision measurements
- Many more things we don't think of

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Atom Chip Experiment
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Landesstiftung BW

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Atoms being loaded into a spiral on the Atom Chip

PostDoc avaliable