IEKP-KA/2014-11

Search for bosonic resonances decaying via a vector-like quark into the all-hadronic final state and bumpbonding interconnection technology for Phase-I Uprade of the CMS experiment

PHD-Thesis

submitted by

Simon Kudella

to Prof. Dr. U. Husemann
Institute for Data Processing and Electronics (IPE)

Second examiner Prof. Dr. U. Husemann
Institut für Experimentelle Kernphysik (IEKP)

DEPARTMENT OF PHYSICS
KARLSRUHE INSTITUTE OF TECHNOLOGY

Karlsruhe, May 28th, 2014

IEKP-KA/2014-11

Dissertation

vorgelegt von

Simon Kudella

Prof. Dr. U.Husemann
Institut für Experimentelle Teilchenphysik (ETP) Korreferent Prof. Dr. M. Weber
Institut für Prozessdatenverarbeitung und Elektronik (IPE)

Fakultät für Physik
Karlsruher Institut für Technologie

Karlsruhe, 28. Mai 2014

Deutsche Zusammenfassung

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Chapter 2

Motivation and theoretical background

2.1 The Standard Model of particle physics

2.2 Physics beyond the Standard Model

2.3 Physics/Upgrade plans of the CMS Experiment

Chapter 3

Large Hadron Collider and Compact Muon Solenoid Experiment

3.1 Large Hadron Collider

3.1.1 Acceleration Complex

3.1.2 Experiments at the LHC

3.2 The Compact Muon Solenoid (CMS) Experiment

3.2.1 The CMS sub-detector systems

3.2.2 The CMS trigger system

3.2.3 The CMS data-processing structures

Part I

Search for heavy bosonic resonances decaying via a vector-like quark into the all-hadronic final state

Chapter 4

Object identifcation

4.1 Jet clustering

4.2 Jet-identification

4.2.1 b-jet tagging

4.2.2 Boosted object jet-identification

4.2.2.1 W/Z/H-jet tagging

4.2.2.2 t-jet tagging

4.3 Lepton-identification

Chapter 5

Heavy bosonic resonances decaying via a vector-like quarks

Heavy bosonic resonances decaying via a vector-like quarks

5.1 Current scientific status

5.2 Theoretical models

5.3 Physics of the $Z' \to tT'$ system

5.3.1 Basic event selection

5.3.2 Reconstruction of the $Z' \to tT'$ system

5.4 Background sources

5.4.1 Top-quark background

5.4.2 QCD-multijet background

5.5 Datadriven QCD-multijet background estimation

5.5.1 ABCD-method

5.5.1.1 Binwise ABCD-method

5.5.1.2 Validation region on data

5.5.2 Variable selection

5.5.2.1 Correlation between variables

5.5.2.2 Shape prediction

5.5.3 Validation of background estimation method on MC and data

5.5.4 Signal contamination

5.6 Statistical and systematic uncertainties

5.6.1 Theoretical and experimental uncertainties

5.6.2 Uncertainties from ABCD-method

5.7 Statistical analysis of data

5.7.1 Analyis sensitivity using $35.9\,fb^{-1}$ of data

5.7.2 Combination with semi-leptonic final-state

5.8 Results

Part II

Bump-bonding technology for the CMS Phase I Upgrade

Chapter 6

Semiconducting pixel detectors for high-energy physics

6.1 Basics on semiconductors

6.2 Pixelated semiconductors as vertex detectors

6.3 Bump-bonding interconnection technology for pixel detectors

6.3.1 Bump deposition

6.3.1.1 Lithographic bump depostion

6.3.1.2 Non-lithographic bump depostion

6.3.2 Flip-chip bonding

6.4 Bump-bonding technologies for the R&D of future particle detectors

Chapter 7

Production of the CMS Phase I Barrel Pixeldetector

7.1 Phase I Upgrade of the CMS pixel detector

7.2 Overview of the KIT production line

7.2.1 Process flow

7.2.1.1 Material selection

7.2.1.2 “Bare Module” production

7.2.1.3 “Bare Module” electrical test

7.2.1.4 Full module gluing

7.2.1.5 Final electrical test

7.2.2 ETP & IPE infrastructure

7.2.3 Production grading scheme

7.3 Bump bonding pre-processing

7.3.1 Bump deposition by external Vendors

7.3.2 Readoutchip cleaning process

7.3.3 Optical inspection

7.3.4 Material selection

7.4 Flip-chip bonding

7.4.1 Quality-assurance tests

7.4.2 Optimization of the tagging subprocess

7.4.3 Optimization of the reflow subprocess

7.4.4 Reworking

7.4.4.1 Void-studies

7.5 Bump bonding post-processing

7.6 Results

Chapter 8

Summary and conclusion

Performance upgrades of colliders always require the development of new particle detectors, to deal with the new challenges coming with such an upgrade. For the Compact Muon Solenoid (CMS) experiment, the upcoming upgrades of the Large Hadron Collider (LHC) to collision energies of 14 TeV and instantaneous luminosities of $\mathcal{L} = 2 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ bring several challenges concerning the particle flux and radiation damage in the detector. To deal with them, the pixel detector of the CMS experiment needs to be exchanged with an upgraded version (CMS Phase I Upgrade). The fourth layer of the new pixel detector will be produced by a German consortium including Karlsruhe Institute of Technology (KIT).

Pixel detectors provide high granularity and good spatial resolution of particle positions, but hybrid sensor-readout solutions require a high density interconnection technology. The bump bonding interconnection technology is able to provide such a density as well as a good mechanical connection between Readout Chip (ROC) and sensor.

Typical bump bonding technologies are based on lithographic bump deposition processes of for example indium or tin-lead solder bumps. Such bump bonding processes are used for the production of the new CMS pixel detector for the Phase I Upgrade. Half of the new fourth pixel layer will be produced at KIT, which has decided to use RTI International as the external vendor for the bumping (see sec. **??**). The bonding will be performed in-house using a Finetech flip-chip bonder that performs both chip placement and reflow process (see sec. **??**).

For the production of the pixel detector modules for the CMS Phase I Upgrade, a cleaning procedure was developed to remove the thick photo-resist protection layer from RTI on top of the bumps (see ch. **??**) placed there to protect the bumps during transport. The cleaning procedure is based on chemical baths of acetone, isopropyl alcohol and water. To handle the bumped ROCs during the cleaning process, special mechanics were designed, including a cleaning tray, a vacuum system, and a grid which keeps the chips from floating. The cleaning process was tuned and the inspections by scanning electron microscope and energy dispersive X-ray spectroscopy showed that there are no photo-resist residuals larger than 1 µm left on the bumps or the chip surface after cleaning.

The standard lithographic bump deposition processes have the disadvantage that they can only be performed on wafer level and are therefore cost-intensive and lack flexibility, especially in the R&D phase of new particle detectors. For this reason, new bump bonding technologies that allow cheaper and more flexible development of pixel detectors are being investigated.

KIT has decided to develop a gold-stud bump bonding process parallel to the production of the new pixel detector. The gold-stud bump bonding technology is a possible candidate for the development of new pixel detectors. Here, a ball wire bonder places gold-stud bumps onto metal pads by thermo-ultrasonic bonding. The flip-chip bonding process is then performed by a flip-chip bonder using thermocompression. Therefore, the gold-stud bump bonding process does not require any lithography at all.

The gold-stud bumping process at KIT is performed using a Kulicke & Soffa IConn ball wire bonder. After a detailed investigation of the process sequence, the bonding parameters and their influence on the mechanical strength and the shape of the gold-stud bumps were studied (see sec. **??**).

To optimize the bump connection to the aluminum surface of the metal pads, a region of high mechanical strength and stability was determined by a systematic variation of the bonding parameters. This study lead to a stable region around a bonding force of 9 g, an USG[1] current of 30 mA and a bonding time of 8 ms, allowing the placement of 30 µm bumps with a mechanical strength of 8.7 g (see sec. **??**). To place bumps on small passivation openings of 15 µm, the parameters needed to be adjusted towards larger USG power, which lead to bump diameters of 35 µm on passivation openings of 15 µm or 18 µm.

In a second optimization step, the long-term stability of the bumping process was iteratively tuned. Therefore, the parameters defining the wire shear process were varied to provide a correct wire shear and wire re-feeding process. This optimization allowed placing more than 4000 gold-stud bumps without any interruption of the process (see sec. **??**) which corresponds to the bumping of a full CMS pixel single sensor or CMS pixel ROC within five minutes.

During the process optimization an unknown error occurred. The so-called "wire-ripping and sparking error" (see sec. **??**) caused the ball wire bonder to apply a voltage of 5000 V to a wire connected to a gold-stud bump. This destroyed almost all the electric circuits on the chip. The error was solved by using a newer and harder wire. To protect the material from the EFO voltage in the future, an insulation layer made of ceramics was designed. It is placed beneath the chip to insulate it from the ground potential of the bonding table. Although the insulation layer cannot protect the Pixel Unit Cell hit by the high voltage pulse, it does protect the rest of the chip.

As another application for gold-stud bumps, a gold-stud bump UBM layer was designed. This layer can be used to create a solder wettable gold surface for power electronics. The bonding parameters were tuned to create very flat bumps with a thickness of only 6 µm. In the context of this application, the vacuum jig of the bonder has been improved by designing an adapter plate that allows fixing smaller dies (see sec. **??**).

Further-more, the flip-chip bonding of gold-stud bumped chips was investigated. The flip-chip bonding at KIT is performed with a Finetech FINEPLACER$^{\mathrm{TM}}$ femto. The goal of the first bonding tests was to reduce the bonding temperature. A reduction of the bonding temperature to 250 °C for 60 s of bonding time was achieved, avoiding any electromigration inside the sensor or chip. Cross-sections through a flip-chip bonded

[1] Ultrasonic Generator (USG)

assembly showed a good metallic connection between the gold-stud bumps (see sec. **??**) but they also showed a systematic misalignment of the flip-chip bonded chips. This is due to the asymmetric and not completely flat top of the gold-stud bumps, which causes horizontal forces during the bonding and a shift of the chips. In a second step, the bonding force was decreased to reduce these horizontal forces during bonding. To provide good connections of all bumps, the bonding force was set to a value of 250 N (see sec. **??**).

Since the reduction of the bonding force was not sufficient to remove the systematic misalignment, an additional step was introduced into the bump bonding process. In this step, the top of the gold-stud bumps is flattened by pressing the bumped side of the chip onto the bonding table of the femto. The parameters of this procedure were tuned to a bonding force of 400 N and a bonding time of 50 s. The bonding temperature was set to 40 °C to avoid any connection between bumps and bonding table. The flattening allows creating a smooth and planar surface of gold-stud bumps, drastically decreasing the systematic misalignment of the chips (see sec. **??**).

The assemblies show typical pull forces of approximately $9-10$ kg ($2.2-2.4$ g per bump). Electrical tests of the connections were only possible with a radioactive source inducing charge into the sensor bulk. They showed a good electrical connection for most of the bumps. Unfortunately, these tests also showed a rotation of the chips during bonding. To solves this problem, it is necessary to improve the vacuum system of the femto. Since the femto is needed for the production of the pixel detector modules for the CMS Phase I Upgrade, this improvement could not be implemented during this thesis.

In addition to the gold-to-gold process, alternative bump bonding technologies like SnPb solder to gold-stud bumps, Pre-coated Powder Sheet (PPS) solder bumps on gold-stud bumps or anisotropic conductive gluing foils were described and partially tested. These techniques also show great potential for the R&D of new pixel detectors (see sec. **??**).

Although the investigations on gold-stud bump bonding are very promising, future investigations could even improve the process. On the bumping side of the process, only minor parts are not optimized yet. With the change to a harder wire, a second systematic process optimization of the mechanical strength is needed to find the optimum parameters. Further more, different wire types can be tested to find the ideal bonding wire.

On the flip-chip bonding side, an additional reduction of the bonding temperature could allow the usage of gold-stud bump bonding for irradiation studies. The flattening process can be further improved by pressing the bumps onto a polished glass plate instead of the bonding table, avoiding any asperities in the flattening process. To avoid any systematic misalignment and rotational movement the vacuum jig and the pick-up tool of the femto need an upgrade. With these improvements and upgrades, a fully working gold-stud bump bonding process for High-Energy Physics (HEP) particle detectors should be easily possible.

List of Acronyms

ACAB Anisotropic Conductive Adhesive Bonding
ADC Analogue-Digital Converter
ALICE A Large Ion Collider Experiment
APD Avalanche Photo Diodes
ASIC Application-Specific Integrated Circuit
ATLAS A Toroidal LHC ApparatuS
BCB Benzocyclobutene
BD Bump Diameter
BH Bump Height
BPIX Barrel Pixel Detector
BSH Bump Shoulder Height
C4 Controlled Collapse Chip Connection
CA Chamfer Angle
CERN Conseil Européen pour la Recherche Nucléaire
CD Chamfer Diameter
CMOS Complementary Metal-Oxide-Semiconductor
CMS Compact Muon Solenoid
CSC Cathode Strip Chamber
CV Contact Velocity
DAC Digital-Analogue Converter
DC Drift Cell
DESY Deutsches Elektronen-Synchrotron
ECAL Electromagnetic Calorimeter
EDX Energy-Dispersive X-ray
EFO Electric-Flame-Off
ESD Electrostatical Discharges
ETH Eidgenössische Technische Hochschule Zürich
FA Face Angle
FAB Free Air Ball
FODO Focussing, nOthing, Defocussing, nOthing
FPGA Field-Programmable Gate Array
FPIX Forward Pixel Detector
FST Force Sensor threshold
HD Hole Diameter
HCAL Hadronic Calorimeter
HDI High Density Interconnect
HEP High-Energy Physics
HLT High Level Trigger
HPD Hybrid Photo Diode

HPK Hamamatsu Hotonikusu Kabushiki kaisha
IEKP Institut für Experimentelle Kernphysik
IPE Institute for Data Processing and Electronics
KIT Karlsruhe Institute of Technology
L1 Level 1 Trigger
LED Light-Emitting Diode
LEP Large Electron-Positron Collider
LEIR Low Energy Ion Ring
LHC Large Hadron Collider
LHCb Large Hadron Collider beauty
LHCf Large Hadron Collider forward
LINAC Linear Accelerator
LS1 Long Shutdown 1
LS2 Long Shutdown 2
MIP minimum ionizing particle
MoEDAL Monopole and Exotics Detector at the LHC
Nd-YAG Neodymium-doped Yttrium Aluminum Garnet
POM Polyoxymethylen
PPS Pre-coated Powder Sheet
PS Proton Synchrotron
PSB Proton Synchrotron Booster
PSI Paul Scherrer Institute
PTFE Polytetrafluoroethylene
PUC Pixel Unit Cell
QCD Quantum Chromo dynamics
ROC Readout Chip
RPC Resistive Plate Chamber
RTI Research Triangle Institute
RWTH Rheinisch-Westfälische Technische Hochschule Aachen
SEM Scanning Electron Microscopy
SD Smooth Distance
SH Separation Height
SPS Super Proton Synchrotron
TBM Token Bit Manager
TEC Tracker EndCap
T Tip diameter
TIB Tracker Inner Barrel
TID Tracker Inner Disk
TIP Tool Inflection Point
TOB Tracker Outer Barrel
TOTEM Total Elastic and Diffractive Cross Section Measurement
UBM Under Bump Metallization
UHH University of Hamburg
USG Ultrasonic Generator
VPT Vacuum Phototriodes
VTT Valtion Teknillinen Tutkimuskeskus
WD Wire Diameter

Acknowledgements

Ohne die Unterstützung verschiedener Personen wäre diese Masterarbeit in ihrer Form unmöglich gewesen.

Ich danke Prof. Ulrich Husemann und Prof. Marc Weber für ihr Engagement, das diese institutsübergreifende und interessante Masterarbeit für mich erst möglich gemacht hat.

Special thanks go to Dr. Michele Caselle and Prof. Ulrich Husemann for their excellent mentoring of this thesis and the long and informative discussions on bump bonding and pixel detectors.

Ich danke Dr. Thomas Blank für die Zusammenarbeit und die stehts offene Tür für sämtliche Angelegenheiten dieser Arbeit.

Für die Einarbeitung in den Ball-Wire-Bonder und die intensive Zusammenarbeit und Unterstützung im Reinraum danke ich Benjamin Leyrer. Des weiteren danke Fabio Colombo und allen Mitgliedern der Fachgruppe für Aufbau und Verbindungstechnik des Insituts für Prozessdatenverarbeitung und Elektronik (IPE) für die Unterstützung im Reinraum. Weiter danke ich Tibor Piller für die zügige Bearbeitung und Fertigung aller mechanischen Teile und Tobias Barvich für die beratende Unterstützung in mechanischen Angelegenheiten.

Dr. Hans-Jürgen Simonis und Stefan Heindl danke ich für die IT-Unterstützung während meiner Zeit am Institut für Experimentelle Kernphysik (IEKP). Weiter bedanke ich mich bei Diana Fellner-Thedens und Brigitte Gering für die Unterstützung in der universitären Bürokratie. Ebenso danke ich Alexandra Jung vom Institut für Technische Physik (ITEP) für die REM- und EDX-Aufnahmen.

Besonders bedanken möchte ich mich bei meinen Kollegen, vor allem aber bei Stefan Heindl und Dr. Thomas Weiler, für die unermüdlichen Korrekturen an dieser Arbeit. Besonderer Dank geht auch an Holger Michelfeidt, Christian Schramm und vor allem Marina Schramm für die unzäligen orthographischen Korrekturen sowohl in englischer als auch in deutscher Sprache.

Für die abwechslungsreiche Überbrückung des Mittagstiefs danke ich Volker Heine, Florian Kassel, Dr. Robert Eber und allen anderen Mitgliedern der Skat- und Kafferunde. Weiter danke ich Hendrik Seitz für ein Jahr allmorgentlicher Fahrradfahrten an den Campus Nord, unabhängig von den Witterungsbedingungen.

Zuletzt danke ich meiner Familie, dem Physiker-Theater Karlsruhe, den "Royal Backwash Babies", der Doppelkopfrunde und vor allem Salome Vogt für das Versüßen meiner Zeit außerhalb des KIT.

Erklärung

Hiermit versichere ich, die vorliegende Arbeit selbständig angefertigt, alle dem Wortlaut oder Sinn nach entnommenen Inhalte anderer Werke an den entsprechenden Stellen unter Angabe der Quellen kenntlich gemacht und keine weiteren Hilfsmittel verwendet zu haben.

Simon Kudella
Karlsruhe, den 28. Mai 2014