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科研費
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研究課題名（和文）Electron Holography Studies of Cadmium Telluride (CdTe)

研究課題名（英文）Electron Holography Studies of Cadmium Telluride (CdTe)

研究代表者
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研究者番号：４０７９２１５６

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研究成果の概要（和文）：電子線ホログラフィー法は半導体材料内の電位分布をナノスケールレベルで一意的、定量的にイメージングできる。一方、CdTeは次世代医療イメージング検出器用の材料として極めて有用と考えられているが、検出器の特性にはまだ改善の余地が多い。その主因はCdTe自体の材料欠陥と半導体―金属接合界面による電気特性の悪化にある。本プロジェクトは電子線ホログラフィー法によりナノスケールレベルでの観察により、CdTeの欠陥による影響を解明し、CdTe検出器の特性改善に寄与するものである。

研究成果の学術的意義や社会的意義
We have measured intrinsic material parameters that were previously unknown. We have also clarified the underlying physics which defines mean free paths in off-axis holography. We have established a collaboration with a local CdTe semiconductor company to continue the research.

研究成果の概要（英文）：The electron holography method can uniquely and quantitatively image the potential distribution in a semiconductor material at the nanoscale level. On the other hand, CdTe is considered to be extremely useful as a material for next-generation medical imaging detectors, but there is still much room for improvement in the characteristics of the detector. The main causes are the material defects of CdTe itself and the deterioration of electrical properties due to the semiconductor-metal junction interface. This project aims to elucidate the effects of CdTe defects by observing at the nanoscale level using electron holography, and to contribute to improving the characteristics of the CdTe detector.

研究分野：Physics

キーワード：holography　semiconductor　CdTe

１．研究開始当初の背景

This project involved electron holography studies of the semiconducting material, cadmium telluride (CdTe).　CdTe is a technologically important material, with great potential for use as a detector material for high-energy radiation owing to its high density and atomic number. However, many of the fundamental material and device properties are poorly understood, and today's devices are relatively unstable. A global-leading producer of detector-grade CdTe crystals is located in Okinawa prefecture, in close proximity to OIST.
Electron holography is a microscopy-based technique which allows quantitative structural and electric field mapping within specimens of interest.　As such, it is an excellent tool with which to explore fundamental material and electrical properties within CdTe devices.

２．研究の目的

Our goal for this project was to apply electron holography to the study of CdTe semiconductor devices.　This required developing competence in preparation of thin electron-transparent lamellae of CdTe, which is rather difficult as CdTe is a delicate, so-called "soft-brittle" material.　Once lamellae have been fabricated, competence must be developed in executing holography measurements, and previously unknown material parameters must carefully measured and documented.

３．研究の方法

A fundamental part of electron microscopy study is the preparation of electron transparent lamellae, but this is particularly important for quantitative holography studies, and is particularly challenging for soft-brittle CdTe.　Indeed, this general soft-brittle nature has been one of the major impediments to the application of CdTe in widespread technological applications.　As such, any learnings we can make here are also generally useful in understanding how to optimally process CdTe.　We invested a lot of effort to optimize the sample preparation, including the application of cryoFIB to minimize the formation of crystallographic defects.　We also collaborated with Tohoku University to optimize the sample preparation process, and to try to quantify the lattice damage using converged beam electron diffraction methods.

We also developed competence, and developed optimum settings for electron holography acquisitions on CdTe material.　Most work was performed using a TFS Titan microscope, operating at 300kV. This microscope was located at OIST, but was not optimized for holography work (for example, possessing only a single biprism at the selected area plane).　Nevertheless, we were able to achieve high-quality holography result son our CdTe specimens.　In addition, we collaborated with Hitachi/Riken to perform electron holography measurements at 1.2MV, via the Atomic Scale Electromagnetic Field Analysis Platform.

４．研究成果

A large proportion of the project effort was spent on optimizing the preparation of electron transparent CdTe lamellae.　We produced most samples using a TFS Helios dual-beam FIB system.　We developed recipes which minimized crystallographic damage to the material, including the use of low-kV ion milling.　Furthermore, we developed a workflow such that we could employ a Hitachi S4000 FIB for cryoFIB preparations.　Bulk CdTe pieces were extracted a room temperature, mounted into suitable grids, and then thinned at a temperature of 96K, to minimize damage to the sample.　Over the course of the project, we have made significant advances in preparation of CdTe lamellae. But this is a very difficult material, and there is more room for optimization in future – we will continue this activity.

We have also performed quantitative electron holography studies of CdTe.　The main activity involved measurement of the mean free path for electron scattering in CdTe.

At the outset, we assumed that this would be a relatively straightforward and fast process. However, we obtained some anomalous results, and thereby found some interesting and previously overlooked phenomena. Thus, this became a quite long and detailed work. The mean free path measure via holography (52nm) was significantly shorter than that measured previously via EELS (192nm). We carefully validated the result, and explained in detail the reason for this difference in measured values. Publication of this mean free path value should have lasting benefit for the community, as it facilitates reliable thickness mapping of CdTe samples, and provides some insight into electron scattering processes inside the material. This work was published in the Journal of Applied Physics, and was selected as a Featured Article by the editors.

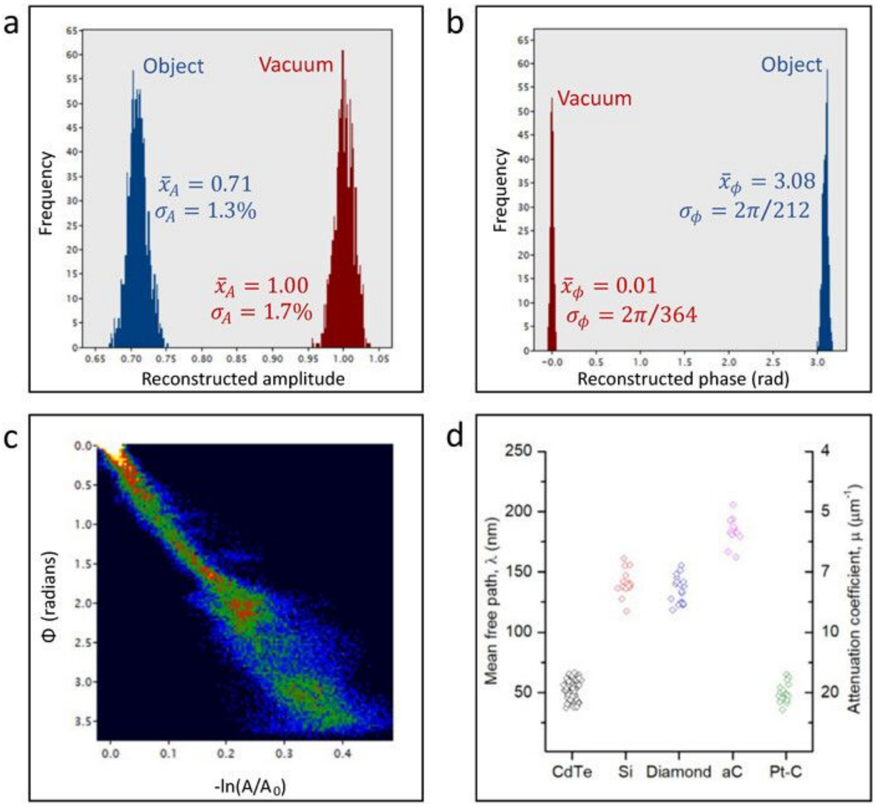

FIG. 2. Amplitude, phase, and mean free path data. (a) and (b) Experimental measurement of CdTe amplitude and phase, respectively. Data from 1000 individual holograms have been averaged to produce the shown distributions, extracted from local regions of interest on object and vacuum regions. (c) Bivariate histogram showing the relationship between the acquired amplitude (log) and phase distributions over an acquired frame including vacuum and varying specimen thickness regions. Such visualizations are helpful for correlating the amplitude and phase signals, assessing acquisition quality and identifying anomalous regions. (d) Calculated mean free path for CdTe, derived from experimental data acquired in a range of different experiments (different specimens, thicknesses, tilts, biprism voltages, magnifications, integration times, reconstruction parameters). Note that we also performed brief reference measurements on single crystal silicon ("Si"), polycrystalline diamond[30] ("Diamond"), amorphous carbon ("aC"), and a platinum-carbon mixed phase layer ("Pt-C").

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In our work to measure the mean free path in CdTe using off-axis electron holography, we encountered some unexpected findings, which changed the emphasis of the project slightly but yielded very interesting and valuable results. We observed that the measurement of the mean free path did not depend at all upon the collection angle or apertures used in the microscope. Also, it appeared that the holography measurements were not any more sensitive to low-energy loss scattering (e.g. phonon scattering) than conventional microscopy measurements. These observations differed from general expectations and some prior work in the literature, so we spent a lot of time to deconvolute the underlying factors. In the end, we identified a fundamental difference in how mean free paths are measured in off-axis electron holography, and clarified how this measurement compares with conventional (intensity-based) measurements like EELS and TEM. We prepared a detailed treatment of the underlying physics and mathematics relating to this problem. We also very carefully measured optical parameters in the microscope, such as effective electron scattering angles at the biprism plane (to evaluate possible "vignetting", whereby electrons are blocked from reaching the detector), as well as the offset distance between the physical biprism and the intermediate image plane in holography. A manuscript was prepared and submitted on this topic, and is currently under review. We have received first (positive) reviewer feedback and are presently working on the revisions.

This work has had a long-tern outcome which will extend beyond the term of the project and outside OIST. Our activities and progress in this project have led to us recently establishing a collaboration with a local company in Okinawa (Acrorad), who are world-leaders in CdTe crystal growth. The skills and insights we have developed during the project on CdTe are proving very relevant for our collaboration with this local company in developing their CdTe technology for medical imaging and astronomy applications. In this context, this Kakenhi project work will have long-term positive consequences, and the research activities will continue into the future.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　1件／うちオープンアクセス　1件）

１．著者名 Cathal Cassidy, Hidehito Adaniya, Tsumoru Shintake	４．巻 129
２．論文標題 Measurement and analysis of the mean free path governing high-energy electron scattering in CdTe, via off-axis electron holography	５．発行年 2021年
３．雑誌名 Journal of Applied Physics	６．最初と最後の頁 055109-1-12
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/5.0036989	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計3件（うち招待講演　0件／うち国際学会　0件）

１．発表者名 Cathal Cassidy, Hidehito Adaniya, Shinichiro Takeda, Tadayuki Takahashi, Tsumoru Shintake
２．発表標題 Electron holography studies of CdTe devices
３．学会等名 CCEM (McMaster University, Hamilton, Canada)
４．発表年 2019年

１．発表者名 Cathal Cassidy, Hidehito Adaniya, Tsumoru Shintake, S. Takeda, T. Takahashi, M. Ageishi, D. Morikawa, K. Tsuda, T. Akashi, H. Kasai, H. Shinada
２．発表標題 Electron holography studies of next-generation medical imaging sensor materials
３．学会等名 OIST-Ryudai Symposium: Medical Sciences: basic medical science to clinical medecine
４．発表年 2019年

１．発表者名 Cathal Cassidy, Hidehito Adaniya, Martin Cheung, Masao Yamashita, Tsumoru Shintake
２．発表標題 Electron microscopy research @ Shintake unit (OIST)
３．学会等名 OIST-Hitachi Joint Symposium (Hitachi Central Research laboratory "Kyousou no Mori", Tokyo).
４．発表年 2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関