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学位（専攻分野）	博士(理学)
学位記番号	総研大甲第662号
学位授与の日付	平成１５年３月２４日
学位授与の要件	数物科学研究科　構造分子科学専攻 学位規則第４条第１項該当
学位論文題目	Surface Photovoltage in Semiconductors Studied with Photoelectron Spectroscopy Using Synchrotron Radiation and Laser
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論文内容の要旨

In this thesis, he describe the newly developed core-level photoelectron spectroscopy, which is based on the combination of synchrotron radiation (SR) and laser light, and the advanced investigation of the surface photovoltage (SPV) effect and its dynamics in a GaAs (100) and two kinds of GaAs-GaAsP superlattices (SLs), which are designed as a spin-polarized electron source. The thesis is composed of five chapters and an appendix.

Chapter 1 includes the introduction of the present work. He has been developing the combinational experiment with SR and laser light. This new and unique method has advantages in studying the transient non-equilibrium conditions. He applied this method to study of SPV effects in a GaAs (100) and two kinds of GaAs-GaAsP SLs, which are designed as a spin-polarized electron source. The SPV effect and its dynamics have particularly been interested in the saturation problem of the spin-polarized electron sources. The purpose of present study is therefore to investigate the SPV and its dynamics using the combination of SR and laser, and to make it clear the relation of the SPV with the saturation problem in the spin-polarized electron sources.

In Chapter 2, the newly developed experimental systems of the core-level photoelectron spectroscopy with the combination of SR and laser light are explained in details. The advantages of this method are excellent surface sensitivity due to few tenth of kinetic energy of the core-level photoelectron, which has only few monolayers of the mean free path in solid, and a capability of temporal profile measurements of the photoelectron spectrum using the pulse character of two light sources. The synchronous of laser and SR pulses was achieved by the Synchro-lock system. The pump-probe experiment has been conducted to observe the time-resolved photoelectron spectra in 11 ns, which is repetition time of SR pulses. To measure the temporal profile of SPV in microsecond range, the system of time-to-amplitude converter (TAC), multi channel analyzer (MCA), and a laser with the frequency of 10 kHz has also been developed.

In Chapter 3, the studies of the SPV effects in *p*-type GaAs (100) are presented. The photoelectron spectrum with laser illumination shifted to higher kinetic-energies about 0.39 eV compared to that without laser illumination at 90 K. It indicates that the shift of the photoelectron spectrum is due to the flattening of the surface band-bending because of the generation of the SPV. The photon-flux and temperature dependences of the SPV are well explained in terms of a thermionic emission model. The temporal change of the SPV has a fast lifetime component of less than 1 ns and a slow lifetime component of more than 11 ns at 125 K. It was found that the temporal profile of the SPV in microsecond range is strongly affected by the sample temperature. On the base of these results, the SPV process consisting of three steps is discussed. The first step is a generation of carriers by photo-excitation. The second step is a transportation of photo-excited carriers. The third step is a recombination of photoexcited carriers. The effects of the first and the second steps are too fast to be observed with the present experimental system. The third step affects the temporal profiles of the SPV in microsecond range. As the recombination process, two ways to pass through the potential barrier are considered. One is the thermionic way and the other is the tunneling one. The observed temporal profiles of the SPV are interpreted using Schottky's barrier model for the thermionic way and a WKB approximation for the tunneling way. The present result is therefore the first evidence to indicate that the annihilation of the SPV at 295 K is dominantly due to the thermionic process and that at 90 K is controlled by the tunneling way.

Chapter 4 gives the SPV effects in GaAs-GaAsP SL samples, which are designed as a spin-polarized electron source. Two kinds of the SLs (SL #1 and SL #16 have surface layers with the doping concentration of 5×10^{18} cm^{-3} and 6×10^{19} cm^{-3}, respectively) were measured by same experimental procedure as described in Chapter 3, and the results are compared with those in the bulk sample. At 295 K, there is no obvious difference between the photoelectron spectra with and without laser illumination. While, at 110 K, the core-level spectra of the SL #1 and the SL #16 shifted to higher kinetic-energies about 0.12 and 0.03 eV under the laser illumination, respectively. In the SLs, no appreciable change of the SPV values was observed in the time range of 1.5 - 11 ns. In the SL #1, the temporal profiles in the microsecond range showed the similar structure as that in the bulk GaAs. These experimental results are also discussed by using the three-step model of the SPV generation-annihilation process. In the SL #1, the transportation of photo-generated carriers would be disturbed in the SL layers and the initial value of SPV was suppressed. In the SL #16, it is supposed that both the initial value and the lifetime of the SPV are suppressed due to the high doping layer in the SL surface, since it makes the surface space-charge region narrower than that in the bulk GaAs. The same measurements described above were performed in a negative electron-affinity (NEA) surface on the GaAs and the SLs. Under the illumination of the laser with the repetition frequency of 10 kHz, the SPV in NEA surfaces was remarkably suppressed in comparison with that in clean surfaces. The escaping of photo-excited electrons from the NEA surfaces decreases the lifetime of the SPV. All experimental results support that the SPV is well suppressed in the SL #16. It is stressed that the suppression of the SPV is important to develop the useful spin-polarized electron photocathode.

In Chapter 5, the concluding remarks are described. It is stressed that the present newly developed core-level photoelectron spectroscopy based on the combination of SR and laser is one of the most powerful methods to measure the SPV effect and its dynamics in semiconductor surfaces. The observed temporal change of the SPV in GaAs (100) with nano to microsecond range is interpreted with the recombination process of photo-generated carriers between the surface and bulk regions. The present results give the clear evidence to indicate that the thermionic process and the tunneling recombination process play important roles in the annihilation dynamics of the SPV. The relation of the SPV with the suppression of the photocurrent from the spin-polarized electron photocathode has been directly confirmed for the first time.

論文の審査結果の要旨

本論文は、放射光とレーザーを組み合わせた内殻光電子分光法の開発とそれを用いたGaAs(100)ならびにGaAs-GaAsP超格子における表面光誘起起電力（Surface Photo Voltage : SPV）効果の研究の成果について書かれており、５章と補足１章で構成されている。

本研究に必要な基本概念は、半導体表面のバンドベンディング、SPV効果、負の電子親和力表面である。これらの応用として、スピン偏極電子源があり、GaAs(100)ならびにGaAs-GaAsP超格子のフォトカソードにおいて放出電子が飽和してしまうという問題を解決するためにはSPV効果の解明が必須である。田中仙君君はこれらの物理現象と応用上の問題点を念頭に、世界的にも極めて質の高いシステムとして放射光とレーザーを組み合わせた内殻光電子分光法を開発して、研究に取り組んだ。

論文では、まず、放射光とレーザーを組み合わせた内殻光電子分光法の実験システムについて詳しく述べられている。特に、表面敏感性と時間分解性を備えている点やナノ秒領域ならびにマイクロ秒領域の２種類の時間分解が可能な点が目立った特徴となっている。次に、GaAs(100)におけるSPV効果の初めての実験結果が示され、励起キャリアーの生成、移動、再結合の過程についてのモデルを基にした近似式を導入することにより、SPVの温度依存性、光量依存性ならびに時間依存性を説明することに成功している。さらに、GaAs-GaAsP超格子の清浄ならびに負の電子親和力表面におけるSPV効果の初めての実験結果が示され、スピン偏極電子源の飽和問題が議論されている。超格子による閉じ込め効果と表面層のバンドベンディング効果の寄与を評価分析し、SPV効果と飽和問題の関係を明らかにしている。補足として負の電子親和力表面の生成方法の記述がある。

このように、本論文は、放射光とレーザーを組合わせた新しい内殻光電子分光法の開発に成功するとともに、それを用いてGaAs系フォトカソードの飽和問題とSPV効果の関係を初めて実験的に明らかにした点で、質の高いものであると判断された。よって、田中君の論文は博士論文に値するものであると審査委員全員が結論した。

約３時間、学位論文の内容説明を聞きながら、博士論文に関する専門分野ならびに基礎的な知識に関する質問を行った。田中君は開発した実験システムの詳細、表面光起電力効果の現象、実測データの解析、スピン偏極電子源としての実用上の問題点など、十分把握していることが確認された。また、学位論文を明解な英文でまとめており、英語に関する学力は十分な水準に達していると判断された。

以上、田中仙君君は博士論文を中心としてその周辺分野まで含めて幅広い学識を有していると判断した。また、公開発表会による最終審査にも合格した。