Analysis of the Implementation for Quantum Hall Effect in Metrology and Sensors Application

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Abstract. The Quantum Hall effect, a remarkable phenomenon in physics, has had a profound impact on metrology and sensor technologies. This paper presents a comprehensive analysis of its implementation in these fields. The historical development of the QHE is traced, from the initial discovery of the Hall effect to the integer, fractional, and quantum anomalous Hall effects. The fundamental concepts, including different classifications and their characteristics, are elucidated. The applications in metrology, such as providing highly accurate resistance standards and determining fundamental constants, and in sensors, like those used in automotive and power systems, are detailed with their underlying principles and results. The limitations, mainly related to extreme experimental conditions, and the promising future prospects, e.g., the search for new materials and expanded application domains, are also discussed. The research is significant as it offers a valuable resource for understanding the current state and potential future directions of the QHE's utilization in metrology and sensor applications.

Keywords: Quantum hall effect, metrology, sensors.

1. Introduction

Klaus von Klitzing, a German physicist who studying the Hall effect of two-dimensional electron gas in an intense magnetic field in 1980, observed that the Hall resistance is quantitative, that is, the Hall resistance value presents a series of precise quantization platforms as the magnetic field changes. This discovery is known as the IQHE [1-4]. Soon afterwards in 1982, American physicists Daniel Tsui and Horst Stormer, while studying two-dimensional electronic systems in semiconductor heterojunction, observed further quantization of Hall resistance at lower temperatures and higher magnetic fields, that is, Hall conductance presents fractional quantization values such as 1/3, 2/5, etc. This discovery is known as the FQHE [3]. Later in 2005, the time after the graphene is isolated. American physicist Philip Kim discovered unusual QHE features while doing research on graphene which never happened on any other conventional semiconductors, that is, the sequence of the plateaus was displaced by a half-integer multiple of 4 for both electrons and holes. Since then, graphene has provided a significant platform for physicists to do researches about the QHE [2].

In 2007, An international team of physicists from Germany and the United States discovered quantum spin Hall effect. By the year of 2012, after years of efforts, the research team of Academician Xue of Tsinghua University using a high-quality Cr-doped (Bi, Sb) 2Te3 topological adiabatic thin film which is grown by molecular beam epitaxy successfully measured the quantum anomalous Hall effect at very low temperature (30mK) and zero magnetic field. The research team also found that QAHE resistance value presents a series of precise quantization platforms as the magnetic field changes. Before Klaus von Klitzing discovered QHE, physicists use a set of physical resistance as the highest resistance standard. However, physical resistance is not a fixed value, its resistance value will change with time and environment. Since QHE was observed, it shows that Hall resistance can be precisely calculated by the formula:

$$R_H = \frac{h}{ie^2} \quad (1)$$

Thus, one of the most famous applications of QHE is to calibrating resistance. After years of research on the quantum Hall effect, quantum Hall devices were made technology is developing rapidly. Based on the GaAs/AlGaAs heterostructure the traditional quantum device fabrication technology has been matured. In practice, the quantum resistance sample is placed in an environment with a temperature of about 1.5K and a magnetic induction intensity of about 10T, and with a measurement current of about 70μA, the uncertainty of Hall resistance at the i = 2 platform can reach the order of 10 to the minus 9. In 2004, the discovery of graphene and other two-dimensional materials has provided new platforms for studying the QHE. Graphene exhibits unique electronic properties that make it an ideal candidate for observing the quantum Hall effect at relatively higher temperatures compared to traditional semiconductor systems. Additionally, efforts have been made to understand the role of spin in the quantum Hall effect, leading to the discovery of the quantum spin Hall effect, which has potential applications in spintronics and quantum information processing [4].

The motivation behind this study is to provide a comprehensive and up-to-date review of the quantum Hall effect's implementation in metrology and sensor applications. By gathering and analyzing the existing research, this study will aim to clarify the current state of knowledge, identify the key challenges and limitations, and explore the future directions for research and development. The remainder of this paper is organized as follows. In the next section, this research will discuss the fundamental concepts of the quantum Hall effect, including its different classifications and the underlying physical mechanisms. Section 3 will focus on the applications of the quantum Hall effect in metrology, presenting the details of how it is used to define resistance standards and its role in determining fundamental physical constants. Section 4 will explore the wide range of sensor applications, from automotive sensors to those used in power systems and magnetic field sensing. Section 5 will address the limitations of the quantum Hall effect, such as the requirement for extreme experimental conditions and the current limitations in its practical implementation. Finally, in Section 6, one will discuss the future prospects, including the search for new materials and the potential expansion of application areas, and draw conclusions about the overall significance and potential impact of the quantum Hall effect in metrology and sensor technologies.

2. Concepts of Quantum Hall Effect

After 40 years of development, the quantum Hall effect has been supplemented and refined in detail and subdivided into different types.

2.1. Integer Quantum Hall effect

The IQHE is based on the quantization of the Landau levels of electrons in a two-dimensional electron gas(2DEG) under a strong magnetic field. When the Fermi level lies between two Landau levels, the Hall conductance exhibits integer quantization. In his research, he founds that the high mobility of 2DEG at low temperature (0.5K) and strong magnetic field (18T) environment, its transverse Hall resistance with the magnetic field changes with a series of natural constants h/e:

$$R_H = \frac{h}{ie^2} = \frac{R_K}{i}, i = 1,2,3 \tag{2}$$

Where h represents Planck constant, i represent constant and R_K represent the von Krieching constant. This quantization is a direct consequence of the quantization of the cyclotron motion of electrons in the magnetic field and the Pauli exclusion principle. The integer quantum Hall effect is robust against disorder and impurities in the system, which is one of the reasons for its high precision in resistance quantization. A typical sketch is shown in Fig. 1.

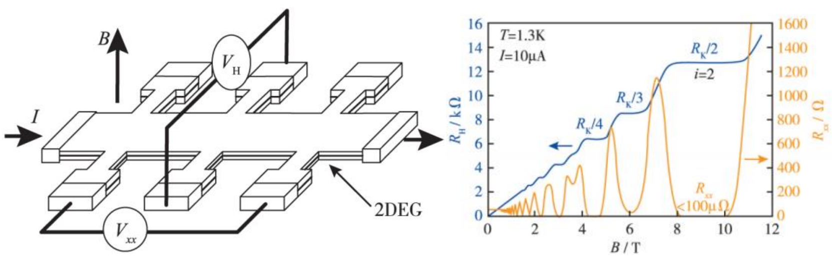

Figure 1. Integer Quantum Hall effect [4]

2.2. Fractional Quantum Hall Effect (FQHE)

The FQHE, on the other hand, arises from the strong electron-electron interactions in the 2DEG. In this case, the electrons form correlated states that lead to the quantization of the Hall conductance in fractional values. The theoretical explanation of the FQHE involves the formation of composite fermions, which are quasiparticles composed of an electron and an even number of magnetic flux quanta. These composite fermions experience a reduced effective magnetic field, and their behavior gives rise to the fractional quantization of the Hall conductance (seen from Fig. 2).

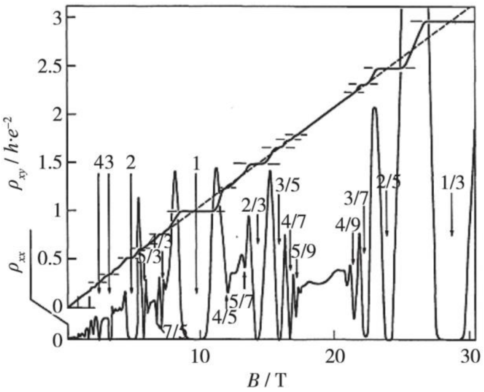

Figure 2. Fractional Quantum Hall effect [2]

2.3. Quantum Anomalous Hall Effect (QAHE)

The QAHE is a more recent discovery and is characterized by the appearance of the Hall effect in the absence of an external magnetic field. It is realized in materials with strong spin-orbit coupling and intrinsic magnetic moments (seen from Fig. 3) [4]. The QAHE is of particular interest as it offers the potential for developing low-power and high-performance electronic devices, as it does not require the application of a large external magnetic field, which is often energy-consuming and requires bulky equipment.

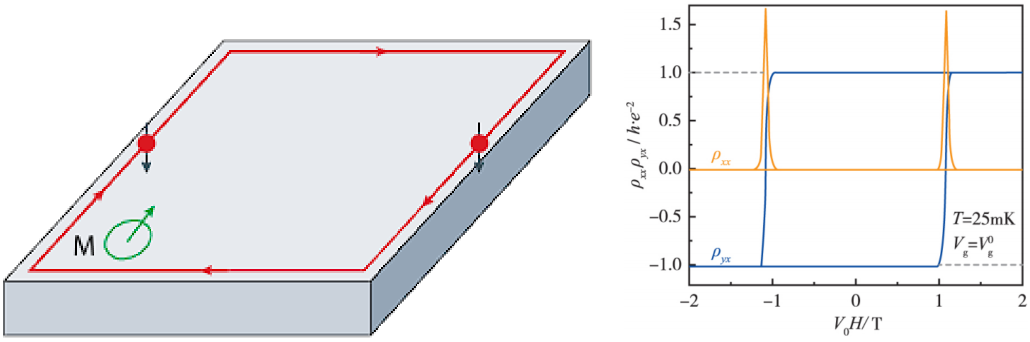

Figure 3. Quantum anomalous Hall effect [4]

2.4. Application scenario

In terms of application scenarios, QHE has found tremendous use in metrology. As mentioned earlier, the precise quantization of the Hall resistance in the IQHE has been adopted as the international standard for resistance. This allows for highly accurate calibration of electrical resistance in laboratories and industries worldwide. In addition to resistance metrology, QHE can also be used to determine fundamental physical constants, such as the fine structure constant. By measuring the quantum Hall resistance and other related physical quantities, an independent determination of the fine structure constant can be made, which provides a valuable test of the consistency of different physical theories.

When it comes to the sensors, QHE offers several advantages. For example, in magnetic field sensors, the QHE can provide highly sensitive and accurate measurements of magnetic fields. The Hall voltage generated in a quantum Hall device is directly proportional to the magnetic field strength, and the quantization of the Hall resistance allows for precise calibration and measurement. In automotive sensors, Hall sensors based on the QHE are used in various applications, such as wheel speed sensors, crankshaft position sensors, and throttle position sensors. These sensors provide reliable and accurate information for the vehicle's control systems, improving the performance and safety of the vehicle. In power systems, Hall effect sensors can be used for current and power measurement. They can be integrated into power electronics devices to monitor and control the flow of electricity, enabling more efficient and reliable power management.

3. Applications

3.1. Applications in Metrology

The application of the QHE in metrology has been a major breakthrough. The precise quantization of the Hall resistance provides an absolute standard for resistance measurement [5]. The international standard for resistance is now based on the QHE, which has replaced the traditional wire-wound resistance standards. The accuracy of the quantum Hall resistance standard is extremely high, with uncertainties reaching parts per billion. This high accuracy is crucial for many fields that rely on precise electrical measurements, such as electronics manufacturing, telecommunications, and scientific research.

In the determination of the fine structure constant, the quantum Hall effect offers a unique method. The fine structure constant is a fundamental physical constant that relates the elementary charge, Planck's constant, and the speed of light. By measuring the quantum Hall resistance and other related quantities, such as the von Klitzing constant, an independent determination of the fine structure constant can be made. This provides a valuable cross-check of the values obtained from other experimental methods and theoretical calculations, helping to validate the consistency of different physical theories [6].

3.2. Applications in Sensors

In modern automobiles, the QHE-based sensors play a vital role. For example, in wheel speed sensors, the quantum Hall sensor detects the rotation of the wheel by sensing the change in magnetic field. As the wheel rotates, the magnetic field passing through the sensor changes, which induces a Hall voltage. The magnitude of the Hall voltage is proportional to the speed of the wheel rotation. This information is used by the vehicle's anti-lock braking system (ABS), traction control system (TCS), and speedometer [7]. The accuracy and reliability of the quantum Hall wheel speed sensor ensure the proper functioning of these safety and performance-related systems. In power systems, Hall effect sensors are used for current and power measurement. A Hall effect current sensor works by passing the current-carrying conductor through a magnetic core. The magnetic field generated by the current induces a Hall voltage in the sensor, which is proportional to the current. By measuring the Hall voltage, the current can be accurately determined. This is useful in power distribution systems, where accurate current measurement is essential for load balancing, fault detection, and power quality monitoring [8]. Hall effect power sensors can also be used to measure the power consumption of electrical devices. They combine the measurement of current and voltage to calculate the power, providing valuable information for energy management and efficiency optimization.

4. Limitations and Prospects

Despite the remarkable achievements of the QHE in metrology and sensor applications, it still faces several limitations. One of the major limitations is the requirement for extremely low temperatures and strong magnetic fields. The IQHE typically requires temperatures in the milli-Kelvin range and magnetic fields of several Tesla. The FQHE demands even lower temperatures and stronger magnetic fields. These extreme conditions make the experimental setup expensive and complex, limiting the widespread practical application of the quantum Hall effect. For example, in industrial settings, it is often difficult to implement such extreme conditions, which restricts the use of quantum Hall effect-based sensors and metrology devices in large-scale manufacturing and process control [9]. Another limitation is related to the materials used. Currently, most of the research and applications of the QHE are based on specific semiconductor materials or two-dimensional materials like graphene. However, the growth and fabrication of these materials with high quality and reproducibility are still challenging. The limited availability and high cost of suitable materials also hinder the commercialization and large-scale deployment of QHE-based devices.

In terms of future prospects, there are several exciting directions of research. One of the key areas is the search for new materials that can exhibit QHE at higher temperatures and lower magnetic fields. Materials with stronger spin-orbit coupling and intrinsic magnetic moments are being actively explored. For example, topological insulators and certain magnetic semiconductors show promise in this regard. If successful, this would significantly reduce the cost and complexity of the experimental setup and open up new opportunities for the practical application of the quantum Hall effect in a wider range of fields [10]. Another promising direction is the integration of the quantum Hall effect with other emerging technologies. For example, combining the quantum Hall effect with superconducting technologies could lead to the development of hybrid devices with unique properties. These devices could potentially have applications in quantum information processing, ultra-sensitive sensing, and high-speed electronics. Additionally, the development of nanofabrication techniques and the miniaturization of QHE devices could enable the creation of more compact and portable sensors and metrology tools, which would be beneficial for applications in fields such as portable electronics, wearable devices, and biomedical sensing.

5. Conclusion

To sum up, this study has provided a comprehensive analysis of the implementation of the quantum Hall effect in metrology and sensor applications. The historical development of the quantum Hall effect, from the discovery of the Hall effect to the more recent QAHE, has been traced. The fundamental concepts, including the different classifications and their underlying physical mechanisms, have been elucidated. The applications in metrology, such as resistance standardization and the determination of fundamental constants, and in sensors, like those used in automotive and power systems, have been detailed with their principles and results. The limitations, mainly related to extreme experimental conditions and material challenges, and the future prospects, such as the search for new materials and the integration with other technologies, have also been discussed.

The research results show that the quantum Hall effect has made significant contributions to metrology and sensor technologies, providing highly accurate resistance standards and reliable sensing solutions. However, there is still room for improvement and development. Looking ahead, the exploration of new materials and the expansion of application areas will be crucial for the further advancement of the QHE. The successful development of materials that can exhibit the quantum Hall effect under more accessible conditions and the integration with other technologies will have a profound impact on various fields, from electronics and telecommunications to quantum computing and biomedical sensing. It is expected that continued research and innovation in this area will lead to the emergence of new and more powerful devices and technologies that will shape the future of modern science and technology.

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